Electron-Density and Electron-Temperature Measurements in Boundary Layers

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Thin-wire Langmuir probes have been used to measure the electron-density and electron-temperature distributions in the nozzle-wall boundary layer of a hypersonic shock tunnel and in the boundary layer of a sharp flat plate located on the nozzle centerline. Experiments were performed in a nozzle-wall boundary layer, with nitrogen as the test gas, in order to obtain a comparison between the results obtained with voltage-swept probes aligned with the flow and constant bias-voltage probes perpendicular to the flow direction. These measurements were performed in the boundary-layer flow because that is the flow environment in which the constant-voltage probes were to be used in flight applications. Only voltage-swept probes aligned with the flow were used in the flat-plate experiments which were performed in preparation for antenna admittance measurements to be made in the future. These experiments were conducted in a test gas composed of argon plus 0.12% nitrogen. The flow conditions for both experiments were such that free-molecular flow theories could be used to infer ion densities from the ion-current portion of the probe characteristics. Electron temperatures measured in these boundary layers were found to be substantially greater than the calculated heavy-particle translational temperature at the boundary-layer edge. For the flat-plate experiments, the electron temperature remained relatively constant through the boundary layer and along the plate. However, the electron temperature in the nozzle-wall boundary layer decreased from the outer-flow value as the wall was approached. The positive ion-density distributions obtained in this latter boundary layer using the two probing techniques (aligned with and perpendicular to the flow) were found to be in good agreement. In addition, the calculated boundary-layer thickness was found to approximate the distance from the wall at which the measured electron density approached a constant value.

I. Introduction

SIGNIFICANT effort, for example Refs. 1–6, has been expended during the past few years in developing techniques for calculating electron-density distributions in boundary-layers flows. However, considerably less effort[7–10] has been devoted to obtaining experimental measurements with which the results of these various prediction techniques can be compared. The purpose of this paper is to describe measurements of positive ion-density and electron-temperature profiles obtained in the nozzle-wall boundary layer of a reflected-shock tunnel and in the boundary layer on a sharp flat plate located in the nozzle inviscid-flow core. The wall boundary-layer experiments were motivated by an interest in obtaining a comparison between boundary-layer electron-density results obtained with voltage-swept thin-wire probes and those obtained with constant bias-voltage probes of the type used to collect flight data.[11] Such a comparison was previously obtained[12] in the nozzle freestream flow and the results of the two diagnostic techniques were found to be in good agreement. The flat-plate boundary-layer experiments were in preparation for S- and X-band antenna admittance measurements to be performed at a later date. The plasmas considered here are neutral in that the positive-ion density is equal to the electron density.

Brown and Mitchner[7] conducted number-density and electron-temperature measurements in the atmospheric pressure, laminar boundary layer on a sharp flat plate and the channel wall for a subsonic, Na K-seeded argon flow. A spectroscopic technique was used to measure the electron-temperature profile and a traversing-probe technique was used to measure the electron-density profile.

Tseng and Talbot[8] performed measurements in the boundary layer of a sharp flat plate located in the inviscid-core flow of a Mach 2.2 argon flow of a low-density plasma tunnel. Their flow conditions were such that thin-wire probes operating in the free-molecular flow regime could be employed to obtain the electron-density and electron-temperature profiles. The boundary-layer thickness over the plate at their measuring stations was on the order of 1.5–2.0 in. thus making rather accurate spatial resolution possible. In addition to the experiments, these authors used the previous work of Chung and Blankenship[13] and Dix[14] to obtain predictions of the electron-density and electron-temperature profiles in the boundary layer and illustrated good agreement between their measurements and predictions.

Sonin[9] and Kaegi and McMenamin[10] have measured the positive-ion distribution in the stagnation region of blunt bodies. Sonin's data were obtained along the stagnation streamline of a blunt-nosed cylinder in a Mach 2.2 steady-state argon flow with a plasma thickness of approximately 0.5 in. and a local Reynolds number of approximately 100. He obtained a well defined ion-density profile in this region showing the merging of the bow shock and the boundary layer. The electron temperature in this region was found to be relatively constant.

Kaegi and McMenamin used a sphere-cone model in the expanding-flow environment of a reflected-shock tunnel with air as the test gas at local freestream Mach numbers of 12 and 13. The ion number-density distribution in the plasma layer was obtained at the stagnation region and at the sphere-cone junction. The local Reynolds numbers in the stagnation region were 300 and 500, respectively, and the plasma thick-

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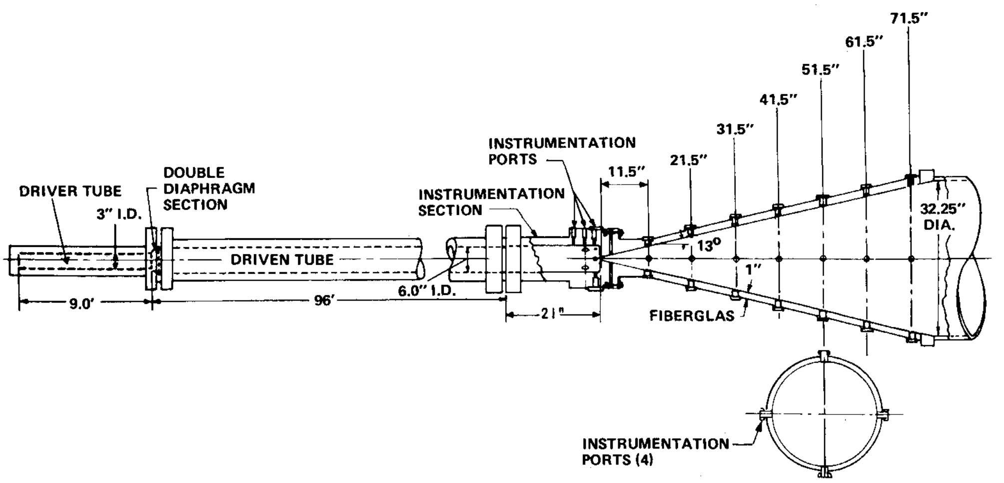

Fig. 1 Schematic of experimental apparatus.

ness was approximately 0.5 in. For this plasma thickness, spatial resolution of the number-density and temperature profiles can be difficult in a relatively short test-time facility such as a shock tunnel.

In addition to the laboratory measurements mentioned above, ion-density distributions measured in the boundary layers of flight vehicles have been reported by Jones[11] for a blunted cone entering the atmosphere at 25,000 fps. He has obtained number-density profiles for an altitude range of 280,000–180,000 ft. The electrostatic probe (constant bias voltage) used in his work was also used in the nozzle-wall boundary-layer experiments reported in this paper in order to obtain a direct comparison between the profile measured with this constant-voltage probe and that measured at the same location with a rake of voltage-swept thin-wire probes.

In Sec. II, the experimental apparatus and procedures are briefly discussed. The boundary-layer measurements obtained in the nozzle-wall boundary layer for an expanding nitrogen plasma are described in Sec. III. Measurements obtained in the boundary layer over a sharp flat plate located in the inviscid core of an expanding plasma of argon plus 0.12% nitrogen are discussed in Sec. IV.

II. Experimental Apparatus and Technique

A pressure-driven shock tube was used to produce a reservoir of high-temperature gas which was subsequently expanded in a conical nozzle constructed of Fiberglas (Fig. 1). As previously noted, two series of experiments were performed. The first series was performed in the nozzle-wall boundary layer at an axial location 34.5 in. from the throat using nitrogen as the test gas. The reflected-shock processed gas was at an equilibrium reservoir condition of 7200°K at 17.1 atm pressure. At this axial location, the Mach number, heavy-particle translational temperature, static pressure, and gas density in the inviscid nozzle flow were calculated to be approximately 8.1, 700°K, 7.04×10^{-4} atm, and 3.0×10^{-7} gm/cm^3, respectively. The dominant chemical species at this location were calculated[15] to be N_2, N, and N^+. A detailed discussion of the nozzle starting process, uniform-flow duration, and boundary-layer growth has been previously presented.[16,17] A chemical analysis of the test gas indicated the following: oxygen less than 0.5 ppm, total hydrocarbons less than 1 ppm, and water less than 0.15 ppm.

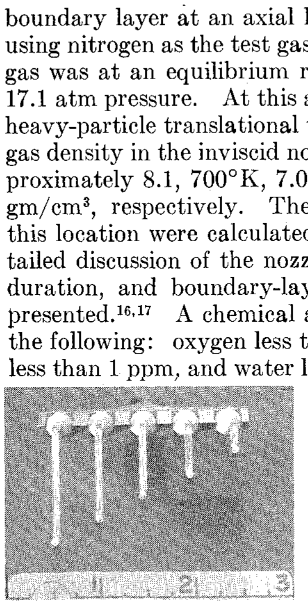

Fig. 2 Probe rake for boundary-layer probing.

The electron-density and electron-temperature distribution in the wall boundary layer were obtained with voltage-swept thin-wire probes aligned parallel to the nozzle wall. For these experiments, the probes were constructed by surrounding 0.004 in. tungsten wires with a quartz envelope, leaving a nominal 0.400 in. length of bare wire exposed. The quartz was fused to the wire at their junction. Immediately prior to each run the probe was ultrasonically cleaned in a dilute solution of sodium hydroxide to remove the tungsten oxide.

The voltage applied to the probe was swept from -5 to $+2$ v (relative to ground potential) in approximately 80 μsec. The voltage sweep was delayed so as to be initiated at any desired time during the uniform-flow period. The ion-current portion of the probe characteristic was used to infer the electron density. The experimental procedure used to obtain the Langmuir-probe data in this nitrogen plasma has been described in detail in previous papers.[17,18]

In addition to the thin-wire probes, the RAM C-1 flight probe[11] was also used in this boundary layer. The probe consists of eight iridium wires with a length of approximately 0.180 in. and a diameter of approximately 0.009 in. The wires are supported on a wedge-shaped dielectric material with the center to center separation distance between adjacent wires of approximately 0.4 in. The wires were located in the nozzle so that their length was perpendicular to the velocity vector. The probe voltage was maintained constant at -5 v relative to the side collectors.

The second series of experiments to be discussed was performed in the boundary layer of a sharp flat plate. The plate was located in the inviscid nozzle flow such that the leading edge was at 22.5 in. from the throat and the top surface was on the nozzle centerline. The test gas used in these experiments was argon plus 0.12% nitrogen. The reflected-shock processed gas was at an equilibrium reservoir condition of 12, 150°K at 30.1 atm pressure. The dominant chemical species at the leading edge of the plate were calculated to be Ar and Ar^+ and the freestream Mach number was calculated to be 15.0. The corresponding heavy-particle translational temperature, static pressure, and gas density were approximately 190°K, 5.4×10^{-4} atm, and 1.38×10^{-6} gm/cm^3, respectively.

A small amount of nitrogen (0.12%) was added to the argon test gas in order to obtain ionization equilibrium in the reflected-shock reservoir prior to termination of the useful test time. As a result of this nitrogen addition, the electron temperatures in the expansion are greater than the argon temperatures because of the electron thermal energy transfer with the vibrational degrees of freedom of molecular nitrogen.[19]

The flat-plate model was 7-in. wide by 30-in. long. The top surface was constructed of plexiglas with the exception of a 1-in. long stainless steel leading edge. Boundary-layer surveys were performed at distances from the leading edge of 6.75 and 19.25 in. using the swept-voltage thin-wire probes discussed previously. At the most upstream location, the flow is considered to be two-dimensional since spanwise static-pressure measurements obtained by Boyer[20] at 5 and 10 in. from the leading edge, for similar flow conditions, indicated that the flow was uniform across the plate. However, for the 19.25 in. location pressure measurements were not obtained, and it is possible that the flow here may not have been two-dimensional.

During all of the experiments noted above an independent measurement of the integrated freestream electron density was obtained just upstream of the probe stations using microwave interferometers operating at frequencies of either 35 or 17 GHz.

III. Nozzle-Wall Boundary-Layer Measurements in Nitrogen Plasma

Voltage-swept thin-wire probes aligned with the flow and constant voltage probes normal to the flow were used to measure the electron-density profile in the nozzle-wall boundary layer at 34.5 in. from the nozzle throat. The magnitudes of the mean free paths in the inviscid flow were calculated using the expressions summarized by Sonin[21] and the previously reported nozzle-flow properties.[15] At the measuring station, the relative magnitudes were: $\lambda_{e-e} \cong 1.7$ cm, $\lambda_{i-i} \cong 0.8$ cm, $\lambda_{e-n} \cong 0.15$ cm, $\lambda_{n-n} \cong 0.03$ cm, and $\lambda_{i-n} \cong 0.012$ cm. The radius of the voltage-swept probes was approximately 0.005 cm and the radius of the constant voltage probes was approximately 0.010 cm. Therefore, all Knudsen numbers, $K_n = \lambda/2r_p$, are greater than 1 except for $(K_n)_{i-n}$ for the constant-voltage probe which is equal to approximately 0.5. It was demonstrated in Ref. 12 that the number-density results are not influenced by this small value of Knudsen number.

Detailed measurements of stagnation-point heat transfer and pitot pressure in the boundary layer had previously been obtained[16] at this location using air as the test gas but for essentially the same reservoir conditions. The side-wall static pressure was also measured and found to be equal to the calculated static pressure in the inviscid flow. From these measurements, it was possible to infer the gas-density distribution in the boundary layer. The density distribution normal to the wall was very uniform until approximately 2.3 in. from the wall at which point it began to decrease rapidly. At about 0.6 in. from the wall the density had decreased to about 20% of the freestream value. Nearer the wall, it appeared to increase but the spatial resolution of the measurements in this region was not good. Using the measured side-wall pressure and temperature the wall density was calculated to be approximately twice the freestream value. Wallace[22] used an electron-beam luminescence probe to measure gas-density distributions in nozzle-wall boundary layers and found profiles qualitatively consistent with that described above. He obtained good spatial resolution in his experiments and found that the density reversal occurs very near the wall (0.01 or 0.02 of the boundary-layer thickness). For the purpose of estimating the mean free paths in the nitrogen boundary layer, the density profile obtained in the air experiments was considered sufficient. Using this information, the boundary-layer mean free paths were estimated to be approximately equal to those cited above for the outer flow. Since the probes were operating in free-molecular flow environments, it was possible to reduce the aligned-probe data using the theory of Laframboise[23] and the normal-probe data using the theory of Smetana.[24]

In performing the swept-voltage probe measurements, care was taken to keep the probe holder far out in the flow to avoid any possible interference effects in the subsonic flow region. The quartz tubing surrounding the probes was bent as shown in Fig. 2. The $\frac{1}{16}$-in. diam tubing used in the probe construction did not permit probing to within 0.060 in. of the nozzle wall. In the case of the constant-voltage probes, however,

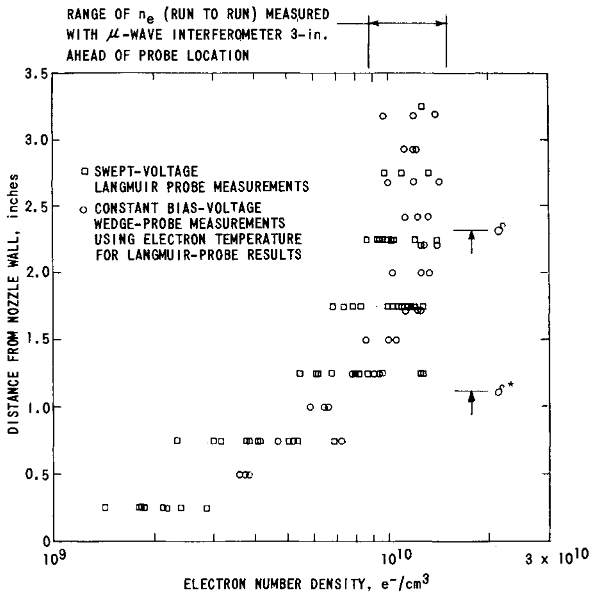

Fig. 3 Electron-density distribution measured in nozzle-wall boundary layer.

the leading edge of the sharp wedge was placed near the nozzle wall. It will be shown later that the number-density measurements appear to be uneffected by the presence of the wedge in the boundary layer. This result was not unexpected since the flow remains supersonic[22] until very near the wall.

The current-voltage characteristics of the swept-voltage probes were obtained from oscilloscope records using an optical comparator. The electron temperature was obtained from the electron-retarding region and the number-density was deduced from the ion-current region of the characteristic. For all of these experiments, the current collected in the electron-retarding region fell on a straight line on a semilogarithmic plot indicating that the electron velocity distribution was Maxwellian in the boundary layer. The procedure used here in reducing the data is discussed in Refs. 25 and 26. The character of the oscilloscope records obtained in the nitrogen boundary-layer flow was very similar to those previously presented.[15]

It is well known[18,27,28] that when the ratio of the probe radius to the Debye length, r_p/λ_D, becomes less than one the indicated number density can be greater than the real value

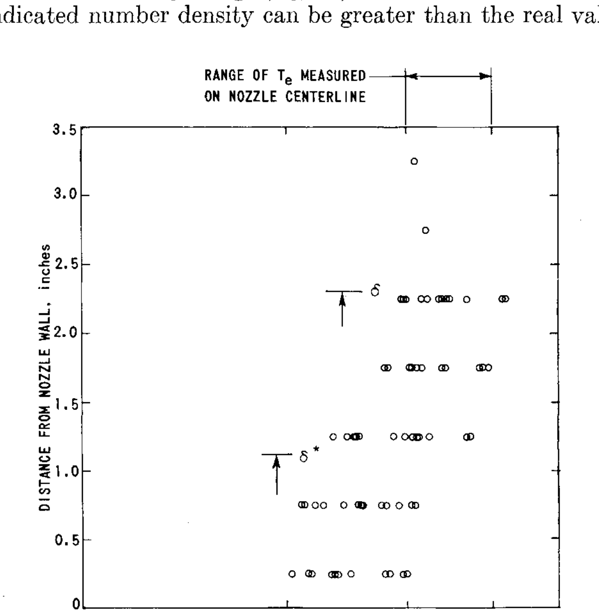

Fig. 4 Electron-temperature distribution measured in nozzle-wall boundary layer.

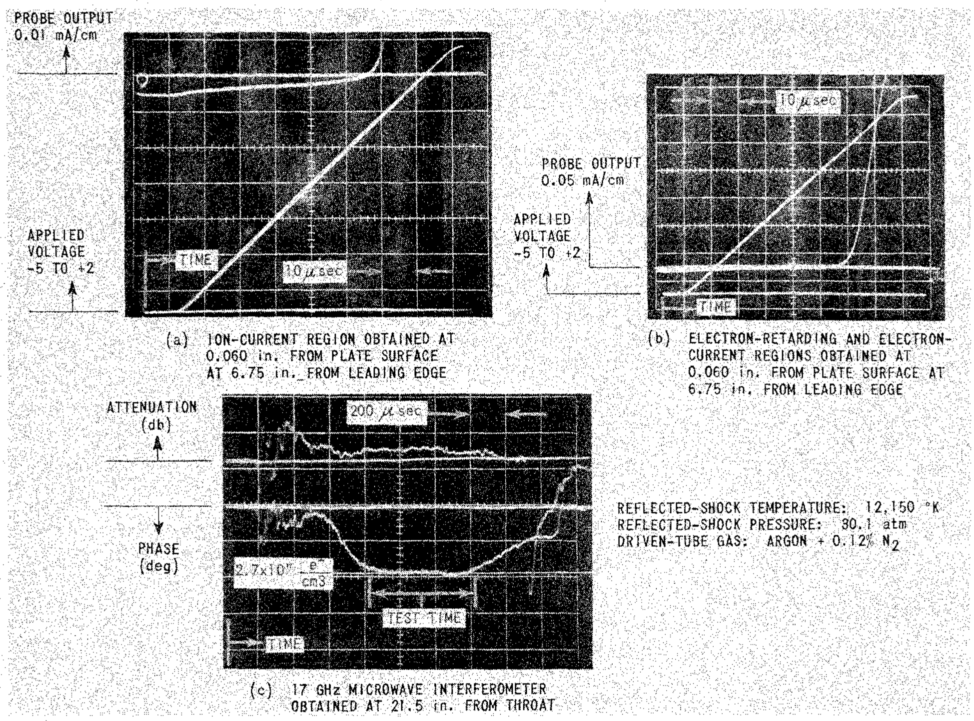

Fig. 5 Typical probe characteristic and microwave-interferometer data in argon-nitrogen plasma.

because of finite end effects.[28] The value of the ratio r_p/λ_D for the present experiments was always greater than 0.85 except for the measurements nearest the wall where it reached a low value of approximately 0.6. It is shown in Ref. 28 that as the velocity and Debye length decrease, the importance of end effects also decreases suggesting that these latter measurements were probably uneffected.

The electron-density distribution measured in the wall boundary layer is presented in Fig. 3. As previously noted, the oscilloscope records obtained in the nitrogen boundary-layer flow for both the swept- and constant-voltage probes were very similar to those previously presented.[15,21] The agreement obtained between the ion-density values determined with the swept-voltage probes and those obtained with the constant-voltage probes appears to be reasonably good. Within the accuracy of the experimental data, the electron-density distribution approaches the measured freestream value at approximately 2.3 in. from the wall. The character of the distribution is qualitatively similar to the measured gas-density profiles discussed earlier in this section. It is difficult to make direct comparisons between the experimental results and theory for several reasons. First, a theory capable of treating the specific problem of interest is not readily available. Secondly, the catalyticity of the wall to electron-ion recombination is not known. However, it is unlikely that electron-ion recombination in the boundary layer would be important at this location since the gas-phase chemistry in the inviscid freestream was shown[15] to be frozen upstream of the measuring station. Essentially the same species are present in the boundary-layer flow and the electron temperatures of the two regions are comparable, which suggests that gas-phase recombination in the boundary layer is probably insignificant.

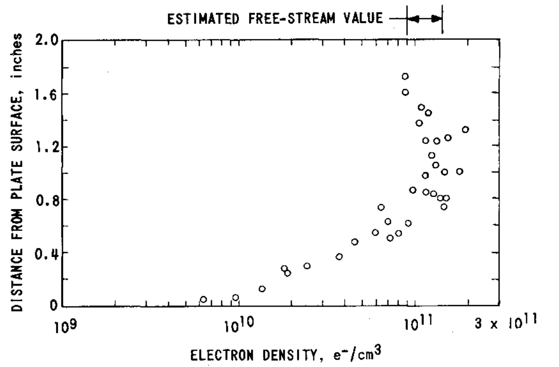

Fig. 6 Electron number density above plate at 6.75 in. from leading edge.

The boundary-layer thickness (δ) and displacement thickness (δ_*) noted on Figs. 3 and 4 were calculated using the method suggested by Burke and Wallace[29] for a turbulent nozzle-wall boundary layer. The boundary-layer and displacement thicknesses calculated in this manner have been shown[15] to be in good agreement with experimental data for reflected-shock reservoir conditions similar to those used here but with air as the test gas. The calculations were also performed for nitrogen and the results indicated that the nozzle-wall boundary-layer growth should be very similar to what it was for air.

Mean values of the electron-temperature measurements presented in Fig. 4 were used to deduce electron densities from the collected-current data of the constant-voltage probe using the theory of Smetana.[23] However, the electron densities deduced using this theory are a weak function of temperature. That is, if 500°K were used as the electron temperature instead of 3500°K, then the electron density would be overpredicted by approximately 15–20% which is within the experimental scatter of the data presented in Fig. 3. From the viewpoint of flight-data analysis this insensitivity is important because it suggests that knowledge of T_e is not essential for reduction of the probe data for the type of probe used here. It should be emphasized that this observation is not necessarily true when obtaining densities from probes aligned with the flow.

The temperature results presented in Fig. 4 show that the electron temperature decreases gradually as the nozzle wall is approached. This trend is consistent with the results obtained by Tseng and Talbot[8] for their flat-plate boundary-layer measurements. They attributed the decrease to loss of high-energy electrons to the plate surface and the inefficiency of recombination energy transfer to the electrons in the close proximity of the surface. It is unlikely that gas-phase recombination played a role in the results presented here but it is possible that some of the high-energy electrons could have been removed by the nozzle wall. However, since the wall was constructed of an insulating material, it seems doubtful that any significant number of electrons would be absorbed by this surface. As was the case with the number-density

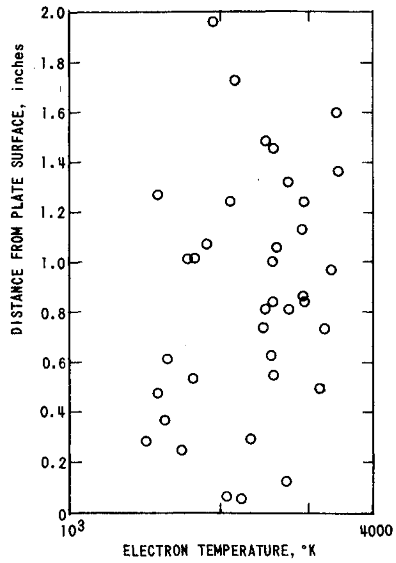

Fig. 7 Electron temperature above plate at 6.75 in. from leading edge.

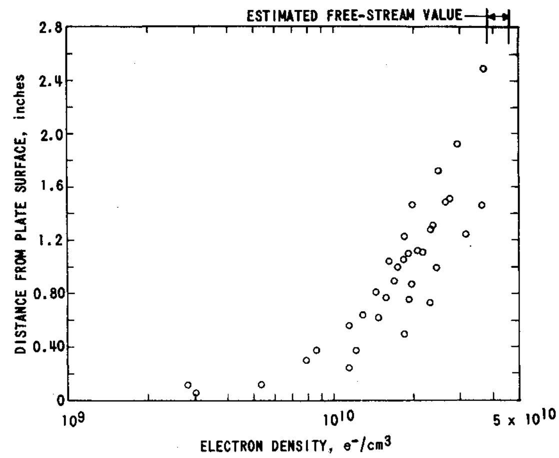

Fig. 8 Electron number density above plate at 19.25 in. from leading edge.

measurements, the scatter in the data is approximately ±15–20% which is greater than previously experienced (±10%) with the thin-wire probes when they were used in the inviscid-flow environment.[15]

IV. Flat-Plate Boundary-Layer Measurements in Argon-Nitrogen Plasma

Boundary-layer measurements of electron density and electron temperature were performed at 6.75 and 19.25 in. from the leading edge of a sharp flat plate placed with its leading edge on the nozzle centerline at 22.5 in. from the nozzle throat. At this axial location, the entire leading-edge span is in the inviscid flow. Spanwise surface-pressure measurements[20] suggested that the flow over the plate was two dimensional as far downstream as 10 in. from the leading edge. Measurements were not attempted at greater distances. Boyer's[20] measurements indicate a significant axial pressure gradient on the plate surface as a result of the outer-flow expansion in the nozzle. Therefore, a theoretical prediction of the number-density profiles and boundary-layer growth measured here should include the influence of the pressure gradient. Such a calculation is beyond the scope of this work and was not attempted.

The voltage-swept thin-wire probes used for these measurements were described in previous sections. The technique for minimizing probe-holder interference in the boundary layer was also the same in that only the $\frac{1}{16}$-in. diam quartz tubing which surrounded the wire was allowed in the boundary layer. A typical swept-voltage probe data record obtained at 0.060 in. from the plate surface is shown in Fig. 5. Also shown is a 17 GHz microwave-interferometer data record obtained 1 in. upstream of the leading edge. The calculated Mach number of the freestream at the leading edge of the plate was equal to 15.0 and the mean free paths were as follows: $\lambda_{e-e} \cong 1.5$ cm, $\lambda_{i-i} \cong 1.7 \times 10^{-3}$ cm, $\lambda_{e-n} \cong 2.7$ cm, $\lambda_{n-n} \cong 7.8 \times 10^{-3}$ cm, and $\lambda_{i-n} \cong 2.4 \times 10^{-3}$ cm. The magnitude of these mean free paths increased with increasing distance from the throat. At the first measuring station over the plate the smallest of these mean free paths, λ_{i-i}, was about 0.5 of the probe radius. It was assumed that the probes were operating in free molecular flow and the free molecular flow theory[23] was used in reducing the data.

Number-density measurements obtained in the boundary layer at 6.75 in. are shown in Fig. 6. The measurements approach the estimated freestream value (0.9–$1.3 \times 10^{11} e^-/cm^3$) at approximately 1.0 ± 0.2 in. from the surface and decrease by an order of magnitude as the wall is approached.

The leading edge of the flat plate (first 1 in.) was constructed of stainless steel and the remainder of the plate surface was plexiglas. It was realized that this construction represents a potential step-function change in surface catalysis. However, results presented by Chung[1] suggest that such a change should not influence the boundary-layer profiles at the two downstream measuring stations for these experiments. The dominant ion in this flow environment was calculated to be Ar^+. In addition, the freestream Ar^+ concentration was found to be frozen well upstream of the plate leading edge. It is thus unlikely that gas-phase recombination of ions and electrons in the boundary layer would be important. However, it is difficult to be certain as to whether or not the plexiglas surface would provide a good catalyst for surface recombination of ions and electrons. If the wall were catalytic, then a diffusion controlled boundary layer would be appropriate and have a number-density profile consistent with the measurements. By contrast, if the wall were noncatalytic and if the boundary-layer electron concentration were frozen at an upstream value, then the measured profile would reflect the boundary-layer gas-density distribution as discussed by Chung.[1] For the flat-plate results presented herein it is difficult to be certain of the mechanism responsible for the mea-

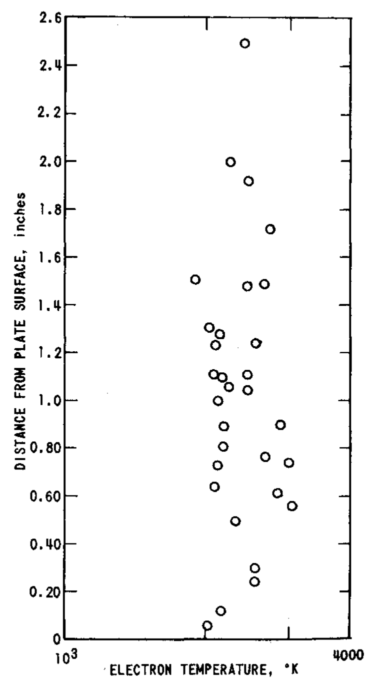

Fig. 9 Electron temperature above plate at 19.25 in. from leading edge.

sured number-density profile and the relationship of that profile to the gas-density profile. The scatter in these ion-density data is less than experienced in the wall boundary layer but consistent with that observed in inviscid-flow measurements.

The flat-plate boundary-layer electron-temperature measurements are presented in Fig. 7. Unfortunately, there was significant scatter in the results of these temperature measurements. It was not possible to observe the trend of decreasing electron temperature through the boundary layer as was seen in the nozzle wall experiments reported here and in the previous flat plate experiments of Tseng and Talbot. On the basis of these measurements it could only be concluded that the electron temperature was relatively constant through the boundary layer at a level considerably higher than the argon translational temperature of approximately 130°K.

Electron-density and electron-temperature measurements obtained at 19.25 in. from the leading edge are presented in Figs. 8 and 9. The number-density measurements suggest a reasonably thick boundary layer on the order of 2.0 in., at which the measured number density approaches the estimated freestream value of $4.0 \times 10^{10} e^-/cm^3$. This estimate of the number-density is included for comparison purposes and was obtained from microwave-interferometer data taken at the measuring station in the absence of the plate. This comparison assumes that the plate does not significantly disturb the flow. The decrease in the outer-flow electron density between the 6.75 and 19.25 in. locations is consistent with that anticipated as a result of freestream gas-density decrease and frozen electron concentration.

The electron-temperature data presented in Fig. 9 suggests that the electron temperature was relatively uniform through the boundary layer. The data scatter is considerably less than experienced at the 6.75 in. location. The explanation for this difference is not clear since the same diagnostic techniques and flow environment were used to obtain the measurements. Comparison of Figs. 7 and 9 suggests that the electron temperature was not only constant through the boundary layer, but it was also relatively constant along the plate. This observation is consistent with a frozen boundary-layer flow in the absence of energy sinks such as thermalization, exchange with vibration, etc., and the absence of energy sources such as recombination.

V. Conclusions

Electron-density and electron-temperature distributions have been measured in the boundary-layer flow of the conical nozzle of a reflected shock tunnel. Nitrogen was used as the test gas and was expanded from an equilibrium reservoir condition of 7200°K and 17.1 atm pressure. The number-density distribution obtained with swept-voltage thin-wire probes aligned with the flow were found to be in good agreement with the distribution obtained with constant-voltage probes placed perpendicular to the flow. In addition, the measured boundary-layer thickness was found to be in good agreement with the value calculated using the empirical prediction technique of Burke and Wallace.

Measurements were also performed in the boundary-layer flow over a sharp flat-plate placed in the nozzle inviscid flow. Argon plus 0.12% nitrogen was used as the test gas for these experiments and was expanded from an equilibrium reservoir condition of 12,150°K at 30.1 atm pressure. Number-density and electron-temperature distributions in the boundary layer were obtained at 6.75 and 19.25 in. from the plate leading edge. Significant gradients in electron density were measured through the boundary layer but the electron temperature was found to be relatively constant. In addition, the electron temperature remained relatively constant along the plate.

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Application of Hot-Wire Anemometry and Digital Techniques to Measurements in a Turbulent Helium Jet

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A two-sensor "hot-wire" probe consisting of a wire and a film is used in connection with an absolute calibration procedure and with digital recording to provide time resolved data on one velocity component $u(t)$ and mass fraction of helium $c(t)$ in a turbulent helium jet discharging at low speed into quiescent air. A careful assessment of probe and system accuracy is provided. The principle new results relate to statistical quantities, i.e., intensities, cross-correlations and spectra, of velocity and concentration on the axis of a turbulent helium jet but some secondary results from other jets are presented.

I. Introduction

THERE are many turbulent flows of practical interest involving significant density fluctuations, e.g., in the wake of bodies in hypersonic flight, in propulsion units employing supersonic combustion, and in boundary layers with external streams having supersonic or hypersonic velocities. In many of these flows measurements of mean quantities such as velocity, temperature, and composition have been made and have been incorporated in methods of analysis. However, few measurements of fluctuating quantities in such flows have been made because of the experimental difficulties involved. In fact, Laufer[1] recently stated "It is somewhat disconcerting, for instance, that since the work of Kistler . . . (1959) . . . no experiments have been reported on turbulent fluctuations in a compressible flowfield above Mach four."

In addition to applied interest in turbulent flows with significant density fluctuations we note that the preponderance of research on the theory of turbulence relates to constant density flows. The necessity of experimental data to support and to guide theoretical developments in the case of turbulent flows with variable density clearly supports an effort to measure fluctuating quantities in such turbulent flows

In view of this situation we have undertaken a program of experimental investigation with the objective of measuring fluctuating quantities in fundamental flows involving significant density fluctuations and under conditions wherein high accuracy could perhaps be realized. These considerations suggest the study of simple, low-speed isothermal flows involving the mixing of two gases of widely different molecular weights. In such flows the density fluctuations are associated with concentration fluctuations. We thereby significantly reduce the problem of frequency response associated with more directly applicable, high-speed flows in which density fluctuations are generally due to temperature as well as perhaps to concentration fluctuations.

Our purpose here is to report the development of a system based on hot-wire anemometry and digital techniques to measure with time-resolution one velocity component and helium concentration and to present the results of its initial application to the measurement of fluctuating quantities on the axis of a low-speed helium jet discharging into quiescent air. In the course of assessment of system accuracy we provide some new data on other jet flows.

Our approach of using the signals from several hot-wires in order to obtain multiple data, e.g., in our case one velocity component and concentration of helium, is not novel. Corrsin[2] put forth and analyzed the possibilities of doing so in

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Index Categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; Research Facilities and Instrumentation.

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