The adverse effect of perpendicular ion drift flow on cylindrical triple probe electron temperature measurements

D. L. Tilley,[a] A. D. Gallimore,[b] A. J. Kelly,[c] and R. G. Jahn[d]
Electric Propulsion and Plasma Dynamics Laboratory, Princeton University, Princeton, New Jersey 08544

(Received 1 March 1993; accepted for publication 3 December 1993)

The cylindrical triple probe method is an attractive technique for measuring electron temperatures (T_e) and electron number densities (n_e) in a variety of plasmas sources. In practice, however, the cylindrical triple probe can be sensitive to sources of error that affect all Langmuir probe techniques. In particular, the presence of an ion drift velocity component that is perpendicular to the probe axis has been known to result in erroneous measurements of n_e. Less obvious, however, is that ion flow perpendicular to the probe has a significant effect on the indicated T_e. The purpose of this note is to make researchers aware of such an effect and to demonstrate a technique which can mitigate it. The approach taken to investigate this phenomenon was to make T_e measurements in the plume of a 20 kW magnetoplasmadynamic thruster with the probe oriented at several angles with respect to the local ion flow.

I. INTRODUCTION

The triple probe method of Chen and Sekiguchi[1] is a convenient and accurate technique for measuring the electron temperature (T_e) and number density (n_e) of a plasma. A triple probe, shown schematically in Fig. 1, consists of three separate electrodes that are electrically configured to eliminate the need for a voltage sweep. This allows for the instantaneous measurements of both T_e and n_e by measuring the voltage between the floating electrode and electrode 1 of Fig. 1 (V_{d2}) and the probe current, I. This measurement capability can be exploited with a probe positioning mechanism to obtain T_e and n_e profiles by sweeping the probe through the plasma.

The ion saturation current is independent of potential when the applied voltage, V_{d3}, is such that $\exp(eV_{d3}/kT_e)\gg 1$, the area of the electrodes are equal, and the electrons are Maxwellian. Under these conditions, the following expression for T_e can be derived:[1]

$$\frac{kT_e}{e} \cong \frac{V_{d2}}{\ln 2}, \tag{1}$$

where k is the Boltzmann constant and e is the elementary charge. The electron number density can be calculated from the measured electron temperature and the triple probe current, which is equal to the ion saturation current of electrode 3. Since no voltage sweep between electrodes is necessary, with a fixed voltage between electrodes 1 and 3 (V_{d3}), $T_e(t)$ can be obtained from $V_{d2}(t)$ with Eq. (1), and $n_e(t)$ from T_e and $I(t)$ using an appropriate ion saturation current model. Note that the instantaneous floating and plasma potential can also be measured with the triple probe.[2]

When the ion saturation current is a function of the electrode potential, the determination of T_e depends on many more parameters, such as the ion–ion collision frequency, electron gyroradius, and the ion flow velocity perpendicular to the triple probe electrodes. It was the purpose of this work to investigate the influence of perpendicular ion flow on cylindrical triple probe measurements of T_e.

II. EXPERIMENTAL APPARATUS

The plasma source for this experiment was a 20 kW steady-state magnetoplasmadynamic (MPD) thruster that used argon as the propellant. The thruster (cf. Fig. 2) has a 2% thoriated tungsten cathode (0.64 cm o.d.) and a flared radiation cooled anode made of graphite with an outer diameter of 10 cm and an inner diameter of 3.5 cm at the exit plane. The thruster was operating typically at discharge currents between 500 and 800 A, at mass flow rates between 6 and 12 mg/s, and with terminal voltages between 15 and 25 V. The thruster was operated in a 6.4-m-long by 1.5-m-diam vacuum tank that is pumped by a 1.2-m-diam oil diffusion pump backed by a Roots blower. Tank pressure was maintained to less than 2×10^{-4} Torr during thruster operation.

Probe positioning was achieved by attaching the triple probe to the end of a pendulum arm that was swept through the plume of the MPD thruster. The stepper motor used to rotate the arm has its axis located 34 cm radially from the thruster axis (cf. Fig. 2) and swept the arm through the plume at a rate of 21 cm/s azimuthally. To study the effect of plasma flow, a small servomotor was used to vary the angle between the probe axis and the thruster axis (cf. Fig. 2). As is shown in the figure, the probe support was configured in a *U shape* such that the axis of probe rotation is located at the midpoint of the

[a]Graduate Student, Department of Mechanical and Aerospace Engineering; currently Research Engineer, Electric Propulsion Laboratory, Phillips Laboratory, Edwards A.F.B., CA.
[b]Graduate Student, Department of Mechanical and Aerospace Engineering; currently Assistant Professor, Department of Aerospace Engineering, University of Michigan.
[c]Manager and Senior Research Engineer, Electric Propulsion Laboratory.
[d]Professor, Department of Mechanical and Aerospace Engineering.

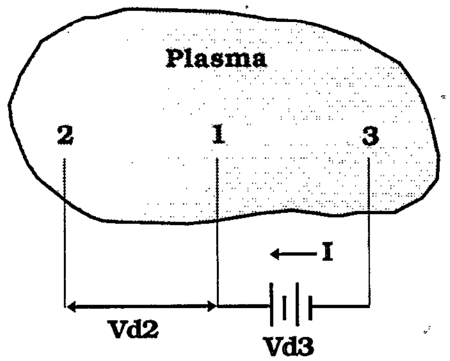

FIG. 1. Schematic of the triple probe.

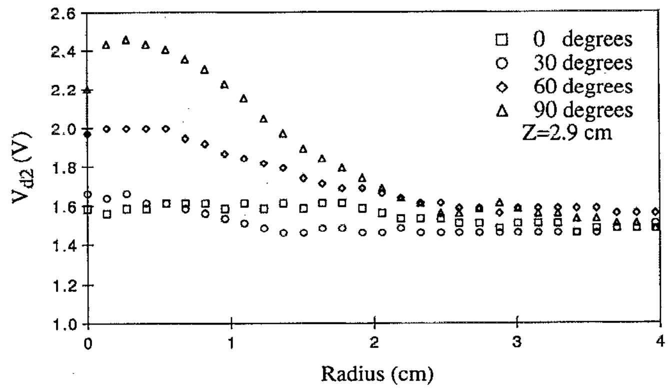

FIG. 3. Output of the triple probe at various angles with respect to the thruster axis (V_{d2}). The probe swept through a plane that was 2.9 cm downstream of the thruster exit plane (J_t=450 A, $\dot{m}$=8 mg/s).

three electrodes. The first 90° bend in the 3-mm-diam alumina tubing probe support is located 3 cm downstream of the axis of rotation.

The triple probe consisted of three tungsten wires configured in a three-in-line fashion within a plane parallel to the pendulum arm axis. The probe dimensions were chosen as a compromise between negligible end effects and sheath interactions, and good spatial resolution [spacing=1 mm, probe radius (r_p)=0.12 mm, and electrode length (L) =5 mm]. A Kepco 100 V, 1 A power supply was used to supply V_{d3}, and two Tektronix AM501 operational amplifiers were used to measure V_{d2} and the voltage from the shunt (a 50 Ω thin film resistor). In all experiments, V_{d3} was set to 14 V. Probe data was collected by a Nicolet 320 digital oscilloscope and transferred to a personal computer for processing. Since contamination of the probe electrode surface is known to seriously affect triple probe measurements,[3] the triple probe used in this study was cleaned via ion bombardment for a few minutes before each test run by flooding the vacuum chamber with argon and maintaining a glow discharge between the probe electrodes and the thruster anode. More details associated with the experimental apparatus can be found in Refs. 3 and 4.

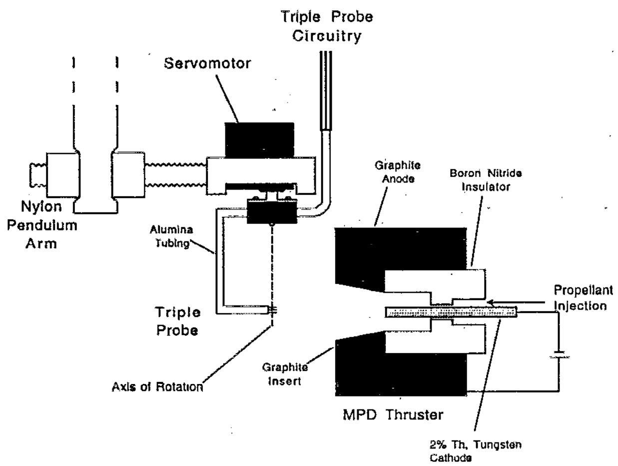

FIG. 2. Thruster and servomotor configuration.

III. RESULTS AND DISCUSSION

It is well documented that supersonic ion flow perpendicular to a cylindrical probe increases the ion current significantly.[5–7] This is because ions are not only collected by diffusion but also from convection due to the ion drift velocity. Typical ion flow velocities, U_i, in MPD thruster plumes correspond to speed ratios, $\mathscr{S}_i(U_i/\sqrt{2kT_i/M_i})$, between 1 and 10.[8,9] Thus, for these experiments the indicated electron number density was observed to be strongly dependent on ion flow conditions (direction and magnitude), as expected.[3] Less obvious, however, is the fact that ion flow perpendicular to the probe artificially increases the indicated electron temperature. In theory, even if more ions are collected at each electrode due to ion drift, if the ion collection process is independent of potential, an assumption made in the derivation of Eq. (1), this effect should cancel out in the determination of the electron temperature. However, as is seen in Fig. 3, this is not the case. Plotted is V_{d2} taken 2.9 cm downstream of the thruster exit plane [cf. Eq. (1)] versus radius from the thruster center line with the probe axis at angles of 0°, 30°, 60°, and 90° with respect to the thruster axis of symmetry. As the figure shows, the orientation of the probe with respect to the ion flow vector has a significant impact on the indicated electron temperature.

In self-field MPD thrusters, the ion flow velocity can be estimated to reasonable accuracy (~50%) by the following equation:[10]

$$U_i=\frac{\mu J_t^2}{4\pi\dot{m}}\left[\ln\left(\frac{r_a}{r_c}\right)+\frac{1}{2}\right], \qquad (2)$$

where μ is the permeability of free space, J_t is the thruster current, $\dot{m}$ is the propellant mass flow rate, and r_a and r_c are the anode and cathode radii, respectively. Using this equation, assuming $T_e \simeq T_i$, which is appropriate for MPD thruster plumes, the value of the perpendicular component of the speed ratio, $\mathscr{S}_{\perp i}(=U_{\perp i}/\sqrt{2kT_i/M_i})$, is approximately ~2 sin θ, where θ is the angle between the probe axis and the local flow vector.

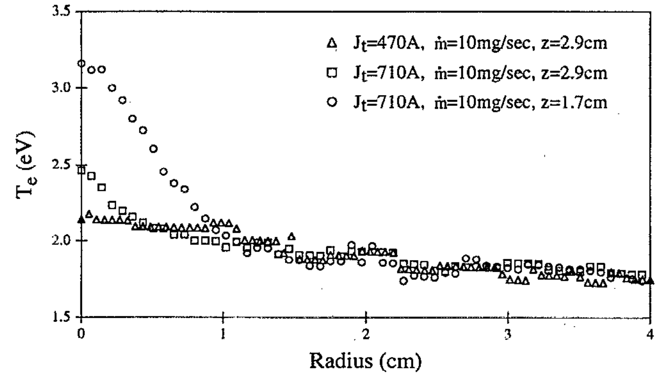

FIG. 4. Typical radial profiles of electron temperature in the near-field plume of the 20 kW level MPD thruster.

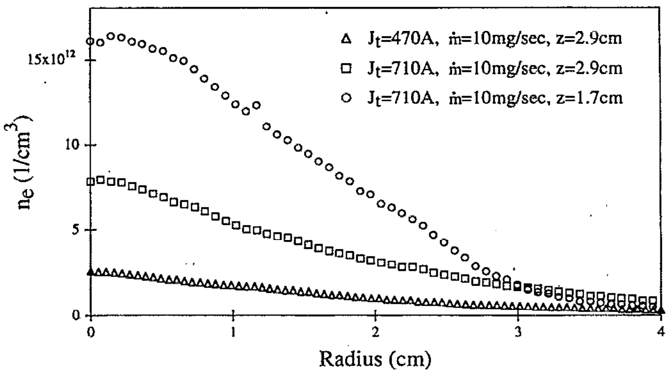

FIG. 5. Typical radial profiles of electron number density in the near-field plume of the 20 kW level MPD thruster (uncertainty was ~60%).

In regions of the plume where the triple probe is aligned with the local ion flow vector, it may be possible to use Laframboise's exact calculations of the ion saturation current to a cylindrical electrode[11] to determine T_e and n_e if certain conditions exist in the plasma. Typical ratios involving the electron Debye length (λ_d), ion–ion mean free path (λ_{ii}), electron–ion mean free path (λ_{ei}), ion gyroradius (r_{Li}), electron gyroradius (r_{Le}), and electron drift velocity (U_e)$-r_p/\lambda_d>10$, $\lambda_{ii}/r_p\gg300$, $\lambda_{ei}/r_p\gg200$, $r_{Li}/r_p\gg10^4$, $r_{Le}/r_p\gg50$, and $U_e/V_{te}\ll1$, where V_{te} is the electron thermal velocity—indicate that Laframboise's model is applicable. Note that the Larmor radii and electron drift velocities were derived from magnetic field measurements made throughout the plume.[4]

In addition to validating the applicability of Laframboise's model, the values of the ratios above suggest that the effects of collisions, magnetic fields, electron drift velocity perpendicular to the probe, sheath interactions, and end effects on the triple probe measurements of Fig. 3 are negligible. Plasma stagnation near the electrodes is expected to be insignificant since the support structure diameter is about one-tenth the size of the local mean free path. Finally, gradient length scales for variations in T_e, n_e, and plasma potential are all sufficiently large as to eliminate gradient effects as a cause for the behavior shown in Fig. 3. Therefore, by the process of elimination, the cause of the effect seen in Fig. 3 is due to ion flow perpendicular to the triple probe axis.

Similar results were obtained in a study with a multi-megawatt, quasisteady MPD thruster[2] where plasma densities were two orders of magnitude larger than those in the 20 kW device at similar exhaust velocities.[3,4] In fact, measurements in the high power MPD thruster suggest that the triple probe is even more sensitive to flow angle at higher number densities ($r_p/\lambda_d>100$).

To interpret this behavior, the results of Godard and Laframboise (see Fig. 5 of Ref. 7) can be used. These results are considered approximate because of their symmetric sheath assumption, and are expected to be accurate for the following conditions: $r_p/\lambda_d\ll1$, or $(\mathscr{S}_{\perp i})^2/\chi\gg1$, or $(\mathscr{S}_{\perp i})^2/\chi\ll1$ where χ is defined as the dimensionless probe potential (eV/kT_e). Although none of these conditions are satisfied in this study or in MPD thruster plumes in general, Godard and Laframboise's calculations do explain qualitatively the results of Fig. 3. Godard and Laframboise show that as $\mathscr{S}_{\perp i}$ increases, the ion current becomes a stronger function of χ, which can lead to the measurement of artificially large electron temperatures.[12] However, the amount of error in measuring T_e predicted by Godard and Laframboise from this effect appears to be significantly less than that seen in Fig. 3. The origin of this discrepancy may be the assumption of a symmetric sheath in their analysis and the fact that their study is not accurate for plasma conditions that were present in these experiments. This assumption also neglects wake effects which may alter the functional dependence of the ion saturation current on the electrode potential. This effect is expected to become more pronounced as the number density of the flowing plasma is increased, a trend that is observed in experiments with high power MPD thrusters.

Therefore, rigorous ion current calculations which account for asymmetric sheaths are needed to resolve this issue. Until such models are developed, however, the one method that currently exists to compensate for T_e and n_e measurement error due to perpendicular ion velocity components is to align the cylindrical triple probe with the ion flow vector.[2,3,6,8] Accurate profiles of n_e and T_e can be obtained by successively sweeping the triple probe through the plume at different angles with respect to the thruster axis, selecting only data at each radial location from the angle corresponding to minimum probe current. Figures 4 and 5 show radial profiles of T_e and n_e, respectively, obtained by this method. The probe was rotated to six different angles with respect to the thruster axis (0°, 10°, 20°, 30°, 40°, and 50°) on successive sweeps through the plume. The estimated uncertainty in these measurements is $\simeq$10% for T_e and $\simeq$60% for n_e, both which are due primarily to unknown T_i.[3] Note, this technique may also be used for obtaining flow angle information in the plume.

[1] S. L. Chen and T. Sekiguchi, J. Appl. Phys. 36, 2363 (1965).
[2] A. D. Gallimore, A. J. Kelly, and R. G. Jahn, J. Propulsion Power 8, 1220 (1992).
[3] D. L. Tilley, A. J. Kelly, and R. G. Jahn, AIAA-90-2667, 21st Inter-

national Electric Propulsion Conference, Orlando, FL, July 18–20, 1990.
[4]D. L. Tilley, M.S. thesis, Dept. of Mechanical and Aerospace Engineering, Princeton University, 1991.
[5]A. A. Sonin, AIAA J. **4**, 1588 (1966).
[6]P. M. Chung, L. Talbot, and K. J. Touruan, AIAA J. **12**, 133 (1974).
[7]R. Godard and J. G. Laframboise, Planet. Space Sci. **31**, 275 (1983).
[8]F. Maisenhalder and W. Mayorhofer, AIAA J. **12**, 1203 (1974).
[9]A. P. Bruckner, K. E. Clark, W. von Jaskowsky, and R. G. Jahn, AIAA J. **12**, 1198 (1974).
[10]R. G. Jahn, *Physics of Electric Propulsion* (McGraw-Hill, New York, 1968).
[11]J. Laframboise, in *Rarefied Gas Dynamics*, edited by J. H. deLeeuw (Academic, New York, 1966), Vol. 2, pp. 22–44.
[12]S. L. Chen, J. Appl. Phys. **42**, 406 (1971).