Measured Exit Plane Properties of a Low-Power Simulated-Hydrazine Arcjet

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Introduction

IN two previous papers on the 1-kW hydrazine arcjet,[1,2] two types of electrostatic probe diagnostics were used at the nozzle exit plane to measure electron density n_e, electron temperature T_e, ion Mach number, plasma velocity u_i, gas temperature T_g, and related quantities. All measurements were performed at 10 A and 50 mg/s propellant mass flow on a NASA Lewis Research Center design,[3] at a specific power of $P/\dot{m} = 22.4$ MJ/kg. These measurements were then compared to the two-temperature chemical nonequilibrium numerical arcjet model of Megli et al.[4,5] The quantities n_e, T_e, and ion Mach number were determined with a novel quadruple electrostatic probe swept across the exit plane, with the probe axis parallel to the flow velocity.[1,6] The plasma velocity was measured with a double electrostatic probe using a technique similar to current modulation velocimetry (CMV).[2,6] Both radial and axial variations of plasma properties were measured and compared to the numerical results.

This Note presents further results for $P/\dot{m} = 19.8$ MJ/kg and $P/\dot{m} = 26.0$ MJ/kg (Ref. 6). The arcjet operating conditions are given in Table 1. This range of $P/\dot{m}$ is representative of the stable operating range of this arcjet on simulated hydrazine (1 mole N_2, 2 moles H_2). The specific impulse is interpolated from data acquired elsewhere on a comparable thruster.[3]

The quadruple probe combines the triple probe method of Chen and Sekiguchi,[7] first applied to electric thruster plumes by Tilley et al.,[8,9] with the crossed probe theory of Kanal,[10] first applied to a single-species plasma by Johnson and Murphree[11] and to a two-species plasma by Burton and Bufton.[1] The quadruple probe was first appled to an electric thruster plume by DelMedico[12] and Burton et al.[13]

The plasma velocity, assumed to equal the ion velocity u_i, is determined by a modification of a technique first developed by Pobst et al.,[14] in which the arc current is briefly interrupted and the resulting deficit in electron density is convected at the plasma velocity and either detected optically[14] or by a double time-of-flight (TOF) electrostatic probe.[2] Radial velocity profiles generated by this technique are accurate to ±500 m/s and provide excellent agreement with those generated by numerical modeling.[4]

Results and Discussion

The effect of varying $P/\dot{m}$ on the anode temperature and the exit-plane quantities T_e, n_e, u_i, and the gas temperature T_g is shown in Table 2 and Figs. 1–3. The quadruple probe location is 2.2 mm downstream of the exit plane, and the uncertainty in the experimental T_e measurement is estimated to be ±1000 K, due to uncertainties in the floating potential measurement and theoretical approximations. T_e decreases on the centerline by 400 K as $P/\dot{m}$ is increased 13% at 10 A arc current and then increases by 1800 K as $P/\dot{m}$ is increased an additional 16% and current is increased from 10 to 11 A, which suggests that T_e is primarily a function of arc current. Previous measurements[6] of the radial variation of T_e show that the profile is flat, i.e., invariant with radius for a given $P/\dot{m}$.

The measurement of n_e as a function of radius shows little variation with $P/\dot{m}$ (Fig. 1). The experimental error in n_e is ±50% (Ref. 6), due both to the standard deviation in the measurements and a propagated uncertainty in T_e. The curves fall within ±12% and are roughly Gaussian, with a peak value of $n_e = 4 \times 10^{12}$ cm^{-3}. This value compares to a density of 1–2 × 10^{13} cm^{-3} found by emission spectroscopy.[15]

The measurement of u_i as a function of radius shows somewhat more variation with $P/\dot{m}$ (Fig. 2). The experimental error in u_i is ±0.5 km/s, due to uncertainties in plasma composition, probe voltage and current, and probe alignment.[6] The centerline velocity is 5.5, 6.6, and 8.0 km/s, increasing with $P/\dot{m}$, and corresponding to mean exhaust velocities based on I_{sp} of 3.9, 4.1, and 4.3 km/s. The increase in u_i of 2500 m/s over the range of operation is significantly larger than the uncertainty in the probe measurement. The bulk of the velocity variation with $P/\dot{m}$ occurs within a 4-mm-diam core flow on axis, with little variation occurring in the viscous region near the wall.

The largest variation with $P/\dot{m}$ occurs with the gas temperature T_g (Fig. 3). The measurement technique overpredicts T_g because the perpendicular probe is off-axis by 2 mm, reducing the current collected. A 10% undercollection decreases the sound speed by 20% and the temperature by 35%, so that the overall experimental uncertainty from the combined quadruple probe and TOF probe measurements is +5/−50%. T_g on the centerline at $P/\dot{m} = 19.8$ MJ/kg is predicted to be only 1200 K, only slightly higher than the anode temperature (Table 2). At $P/\dot{m} = 22.4$ MJ/kg, T_g increases on the centerline to 3000 K, and at $P/\dot{m} = 26.0$ MJ/kg, T_g = 7000 K. The profiles are roughly Gaussian.

These results are in approximate agreement with previous results by Zube and Myers[16] of spectroscopically determined temperatures within the nozzle of a similar arcjet, operated at 9 A (21.0 MJ/kg) and

Table 1 Operating range of 1 kW hydrazine arcjet

Power, W	Current, A	Mass flow rate, mg/s	$P/\dot{m}$, MJ/kg	Specific impulse, s
1188	10	60	19.8	397
1120	10	50	22.4	414
1170	11	45	26.0	440

Table 2 Operating temperatures of 1 kW N_2/H_2 arcjet

$P/\dot{m}$, MJ/kg	Arc current, A	Anode temp, K	Centerline T_e, K
19.8	10	1160	7300
22.4	10	1220	6900
26.0	11	1320	8700

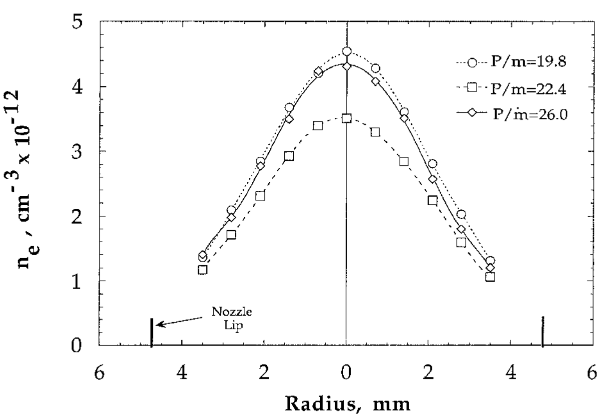

Fig. 1 Radial n_e profiles measured by quadruple probe for the three thruster operating conditions examined; uncertainty in n_e is ± 50% and is not shown.

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Table 3 Comparison of centerline (x = 2.2 mm) n_e and T_e measurements of this study with the numerical exit-plane predictions of Megli et al.[4]

	Experiment					Numerical model			
Case	$P/\dot{m}$, MJ/kg	n_e, cm^{-3}	T_e, K	u_i, km/s	T_g	n_e, cm^{-3}	T_e, K	u_i km/s	T_g
1	19.8	4.6×10^{12}	7300	5.5	1200	3.5×10^{14}	3250	6.9	3000
2	22.4	3.5×10^{12}	7000	6.5	3000	3.1×10^{14}	3030	6.7	2750
3	26.0	4.3×10^{12}	8700	8.0	7000	3.2×10^{14}	3160	6.8	2850

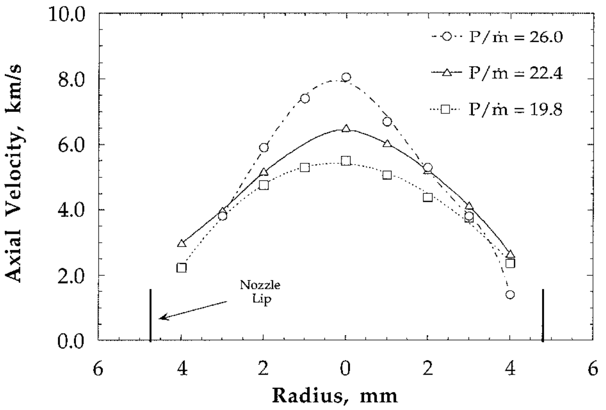

Fig. 2 Radial profiles of the plasma axial velocity u_i measured by quadruple probe for three different thruster specific powers $P/\dot{m}$; error bars are not shown, but are typically ± 0.5 km/s.

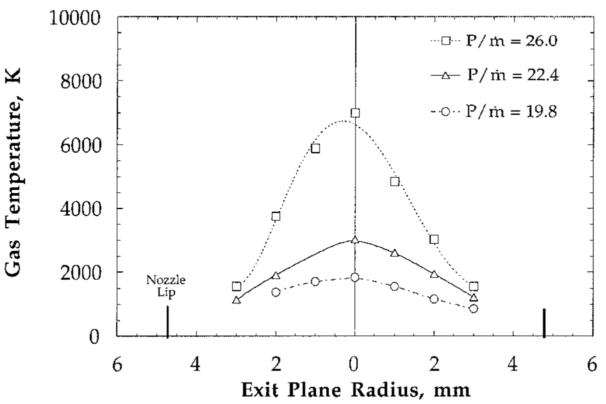

Fig. 3 Estimated gas temperature profiles based on measurements of u_i and $u_i/c_{m,\mathrm{H^+}}$ by quadruple probe for three values of thruster specific power; uncertainty in T_g estimates is +5/− 50%.

12 A (28.0 MJ/kg). They found, at a location 3.3 mm upstream of the exit plane, a nitrogen atom excitation temperature of 8400 K (9 A) and 10,000 K (12 A). The nitrogen molecule vibrational temperature was 2300 K at both currents, and nitrogen molecule rotational temperatures were 2000 K (9 A) and 2600 K (12 A), with the latter to within ±12.5%. The corresponding measurements of T_e and T_g observed here for 10 A and $P/\dot{m} = 22.4$ MJ/kg are $T_e \sim 7000$ K and $T_g \sim 2500$ K. Zube and Myers[16] did not observe the 7000 K +5/−50% temperature on centerline indicated here for $P/\dot{m} = 26$ MJ/kg, suggesting that the probe considerably result overstates T_g at this condition.

A comparison of these measurements with numerical model predictions[4] of n_e and T_e is shown in Table 3, for similar I and $\dot{m}$. The experiments were conducted with the probe centered at an axial location of $x = 2.2$ mm, and the model predictions represent centerline exit plane results. Although the electron densities differ by ~2 orders of magnitude due to the large axial gradient near the exit plane, the data fall between spectroscopic measurements at the exit plane[15] and electrostatic probe measurements made 40–100 mm downstream.[17] The trends in n_e are very similar for the model and experiments. Similarly, the trends in the electron temperature measurements and model predictions are the same, despite the different magnitudes in T_e.

The model axial velocity predictions, despite the fact that the model predicts increased I_{sp} with increased $P/\dot{m}$ similar to the measured results,[4] vary less than ~2% for the range of specific power investigated in this study (Table 3). This could be an indication that the density profiles in the arcjet plume and those predicted by the model may be vastly different, a distinction we were unable to detect.

Table 3 also shows centerline values of the predicted gas temperature T_g at the exit plane vs the T_g measurement. The apparent large increase in the experimental values of T_g with increases in $P/\dot{m}$ may imply a corresponding decrease in the centerline bulk gas density, a trend consistent with the earlier argument that the plasma density profiles of the model and experiment may be quite different despite the accurate model prediction of I_{sp}.

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