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Abstract

In the attempt to fill the performance niche between the arcjet and Hall thruster, we propose the use of a helium arcjet to neutralize Hall thrusters. Since the arcjet is a high plasma density device, one arcjet can potentially neutralize a cluster of Hall thrusters. In this preliminary study, we used a surrogate planar anode in the place of a Hall thruster anode to determine the effects of drawing electron current from a low power arcjet plume on the operation and performance of the arcjet. In all tests we are able to draw currents to the surrogate anode that were greater than the arc current. It is found that biasing the surrogate anode does lead to a perturbation in the arcjet discharge voltage, in some cases resulting in a voltage decrease of up to 40%. The helium arcjet exhibits arc voltage instabilities in the same spectral range of the instabilities that are intrinsic in Hall thrusters. We find however, that these arcjet instabilities decreased in strength and in bandwidth when a bias is applied to the anode. The effect of biasing on the overall arcjet performance (e.g., thrust, specific impulse) is still under investigation. However, preliminary studies made using an impact pressure probe confirms that there is little compromise in the arcjet thrust during the current draw. The use of laser-induced fluorescence to measure the velocity of the arcjet plume flowfield during an applied bias was hindered by the finding that the lower energy state of the helium transition used for the LIF measurements was effectively depopulated by the biasing – a result supported by optical emission measurements of the plume.

I. INTRODUCTION

A broader range of space missions are enabled by a propulsion system that can provide a thrust and specific impulse that lies somewhere between that realized by low power arcjets, or Hall thrusters. At present, modern arcjet thrusters cannot achieve a specific impulse beyond about 600 sec. Modern Hall thrusters do not extend specific impulse too far below 1500 sec. Furthermore, there is a vast difference in the thrust to power ratio generated by these two plasma propulsion sources. We propose that a hybrid Hall thruster – arcjet thruster package where the arcjet serves to neutralize the ion beam, can fill this operating envelope to enable a wider range of missions as a high density neutralizer of large Hall thruster clusters. Such an arcjet neutralization concept for a Hall thruster is schematically illustrated in Fig. 1. It is proposed that the arcjet plume will provide the electron current needed for efficient operation of the Hall thruster, provided that the potential needed to be established in the plume of the Hall thruster does not greatly exceed that potential typically seen in Hall discharges (~25-40V).

Since an arcjet plasma is a high plasma density device ($n_e \sim 10^{12} - 10^{13}$ cm^{-3}) that can support and amplify electron current through volume ionization, it can potentially neutralize multiple Hall thrusters in a cluster configuration. For highest optimum cluster performance, a high thrust efficiency arcjet is needed. For this reason, we propose to examine the response of a helium arcjet plume in its ability to serve as an electron current source at low draw potentials. Helium arcjets are known to have thrust efficiencies near 60% due to the absence of frozen flow losses, and detailed studies of its plume structure have been recently published [1,2]. It is noteworthy that a hybrid arcjet-Hall cluster is expected to require less power and has a lower specific mass than a pure Hall thruster cluster that provides the same thrust. However, in exchange for these benefits, the hybrid arcjet-Hall thruster

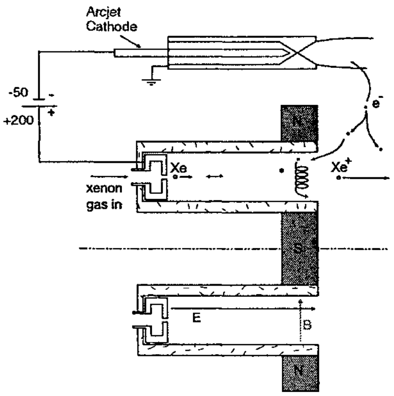

Fig. 1. Schematic for the hybrid arcjet-Hall thruster concept.

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power supply is measured across a shunt resistor with a DC multimeter. Figure 3 shows a picture that depicts the relative positions of the arcjet and copper substrate. During all tests, the substrate is electrically isolated from the arcjet and its supporting structure.

The thrust of the arcjet is measured with an impact pressure probe. Previous studies show that the thrust measured by integrating the impact pressure profile agrees very well with the thrust measured with a thrust stand [9]. A detailed description of the probe is given in Ref 9. Figure 4 below gives a schematic that illustrates the experimental setup for these impact pressure studies. The copper impact pressure probe is 28.6 mm in length and 15.9 mm in diameter with an opening at the tip of 0.51 mm in diameter. The probe tip is attached to a copper collar-body assembly with the required coolant connections and placed on a translation stage that moves horizontally with respect to the arcjet. The pressure profiles are taken within 0.5 mm of the exit plane of the arcjet, and the probe is water cooled to withstand the arcjet plume environment. The pressure within the pitot probe test volume is measured by use of a 0-13,332 Pa MKS capacitance manometer. The probe is moved in increments of 0.25 mm, and it pauses between 5 to 10 seconds at each position. It takes approximately 20 minutes to scan across the exit plane of the arcjet. The manometer is read with a sample rate of 1 kHz.

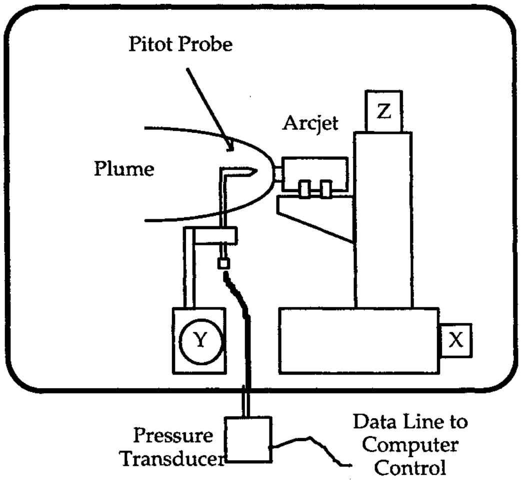

Fig. 4. Experimental setup for the impact pressure probe measurements.

III. RESULTS AND ANALYSIS

A. Arcjet Operation

The arcjet voltage and the surrogate anode current are monitored as the voltage applied to the anode is varied. Figures 5 and 6 show the amount of current extracted from the hydrogen and helium arcjet plume while biasing the surrogate anode. In these experiments, the mass flow rate is a fixed parameter (13.7 mg/s H_2 and 36.2 mg/s He) while the arcjet is operated at various arc discharge current levels. It is apparent that in almost all cases studied, currents greater than the arc current itself can be extracted from the arcjet plume. Specifically, the extracted electron current can be up to 120% of the arc current for the hydrogen arcjet plume and 134 % of the arc current for the helium arcjet plume. However, it is noteworthy that for either arcjet propellant, appreciable currents are not extracted until the anode voltage is above 30V. As the surrogate anode voltage is increased, the amount of extracted current is found to increase nearly exponentially, and then reaches a point where further increases in voltage do not result in increases in the drawn electron current (saturation).

As shown in Figs. 7 and 8, the arc discharge voltage is found to generally decrease as the surrogate anode

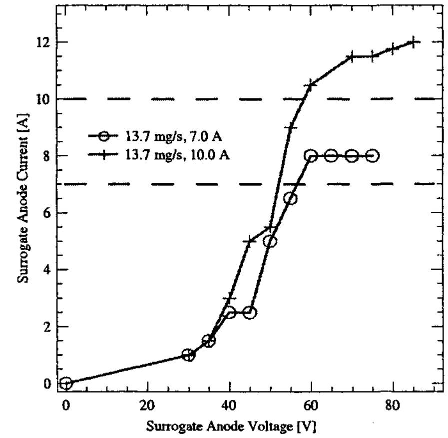

Fig. 5. Neutralization current provided as the surrogate anode voltage is increased (hydrogen arcjet plume).

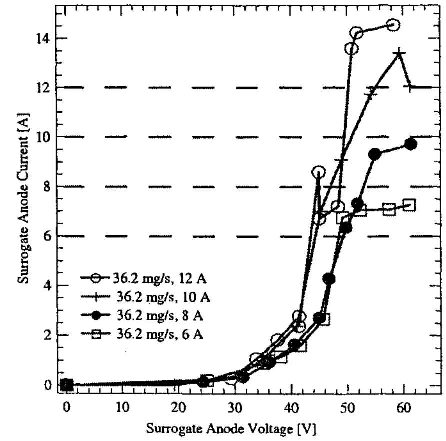

Fig. 6. Neutralization current provided as the surrogate anode voltage is increased (hydrogen arcjet plume).

B. Arcjet Fluctuations

Previous studies of arcjets operating on helium propellant mentioned that the arc voltage fluctuates during operation [2, 10]. These voltage fluctuations cause fluctuations in thrust and other flowfield properties. In this study, the arc voltage was monitored with a Tektronix P5200 High Voltage Differential Probe and acquired into a DAQ5120 card in a PC. In these analyses we examined fluctuations up to 10 MHz. Figure 9 shows part of the spectral amplitude (logarithmic scale) of the low-frequency fluctuations with an arc current of 10 A and a mass flow rate of 27 mg/s for helium and 13.7 mg/s for hydrogen. The hydrogen arc voltage is 150V and the helium arc voltage is near 65V. At these low frequencies the differences between the two are evident. The helium arcjet shows a broadband feature near 120 kHz and its harmonic near 240 kHz. The hydrogen arcjet only has a broadband feature near 300 kHz and a sharp peak near 180 kHz. Also, a comparison of the amplitudes shows that the low-frequency fluctuations are stronger in the helium arcjet. At the higher frequencies, the helium arcjet has a broadband feature centered near 2 MHz which is not present in the hydrogen arcjet, and the strength of the fluctuations are of the same magnitude. Also, it should be noted that the helium arcjet has drift that occurs on time scales measured in minutes. When the arcjet transitions to a different voltage, different frequency components dominate. The low frequency fluctuations continue to dominate, but the broadband features are not always at the same location, though they are always present and in the same hundreds of kHz region.

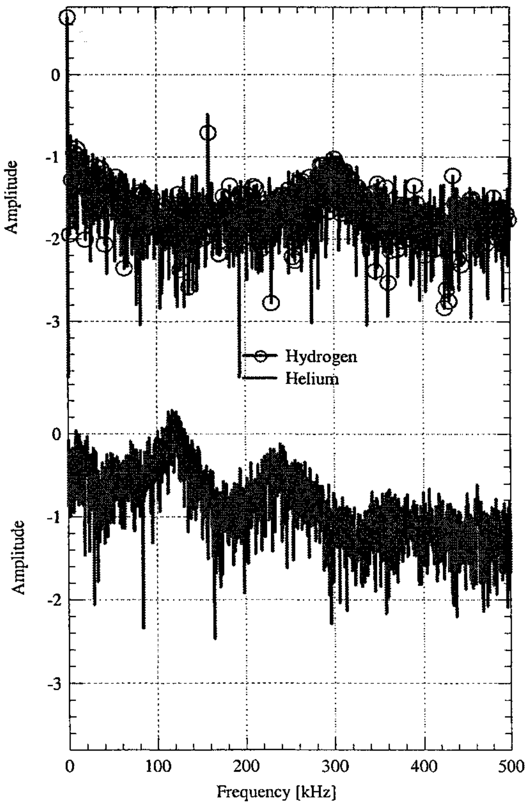

Fig. 9. A comparison of the arc voltage power spectra for the hydrogen (13.7 mg/s, 10 A) and helium (36.2 mg/s, 10 A) arcjets.

Further measurements were taken to determine the effects of changing the mass flow rate and arc current on the unsteady helium arcjet behavior. Figure 10 shows the low frequency fluctuations for different mass flow rates. Increasing the mass flow rate increases the strength of the low-frequency fluctuations. All the spectra have a broadband feature that spreads out from DC to between 300 and 500 kHz. The lower flow rate has a broadband feature near 500 kHz that is not present at the higher flow rates. The higher flow rates show the emergence of a broadband feature near 250 kHz, and a increasingly perceivable decrease in intensity at 300 kHz. With changes in the arc current, the trends are not as clear (see Fig. 11). These data were taken at a flow rate of 45 mg/s, and the fluctuation strength peaks near 8.0 A. Once again, there is a broadband spectrum from near DC to 500 kHz with a weak peak near 300 kHz. These results suggest that lower flow rates are preferred, if it is desired to operate a helium arcjet with weaker low frequency fluctuations.

The arc voltage fluctuations changed somewhat when the arcjet provided electron current to the surrogate anode. In the case of hydrogen propellant, the low frequency fluctuations below 300 kHz increased in strength. There were no substantial differences for high frequency fluctuations. The changes in the fluctuation spectra for the case of a helium flow were somewhat more dramatic in comparison. These are shown in Fig. 12. For the case shown, the arc current is 10 A and the surrogate anode current is 13A. In general, the intensity of the fluctuations decreased across the entire spectrum from 5 MHz to almost near DC, although there is the emergence of a peak at about 450 kHz.

C. Impact Pressure Measurements

In addition to monitoring changes in the fluctuating nature of these arcjets, we also monitored performance changes while the plume provided current to the anode. That the helium arcjet is able to attain higher thrust efficiencies in comparison to arcjets operating on other propellants [2,10] is demonstrated in the thrust measurements conducted with the impact pressure probe. Figure 13 and 14 depict the variation in the thrust, specific impulse, and thrust efficiency at 10 A discharge current with mass flow rate. As expected, the thrust increased with the increase in mass flow rate, with the

Table 2. Comparison of arcjet performance when drawing current from cathode plume

Flow Rate mg/s	Arc Voltage V	Arc Current A	Anode Voltage V	Anode Current A	Arc Thrust mN	Specific Impulse s
36.2	67	10	0	0	163	461
36.2	55	10	50	13	157	444
27	55	10	0	0	122	459
27	49	10	50	13	124	471

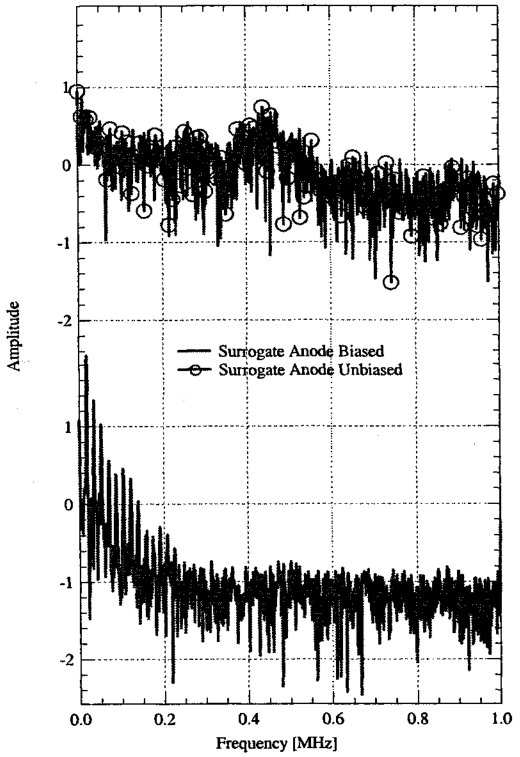

Fig. 12. **Arc voltage fluctuations with and without the bias on the surrogate anode.**

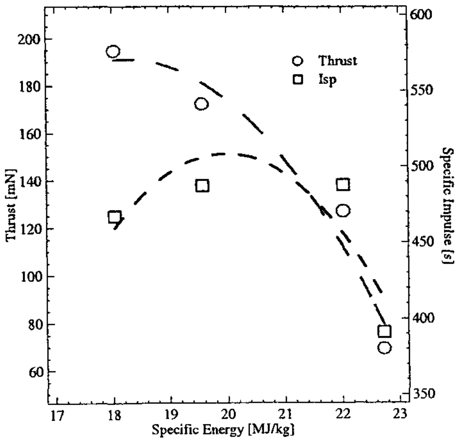

Fig. 13. Thrust and specific impulse of the helium arcjet with a current of 10.0 A and various mass flow rates.

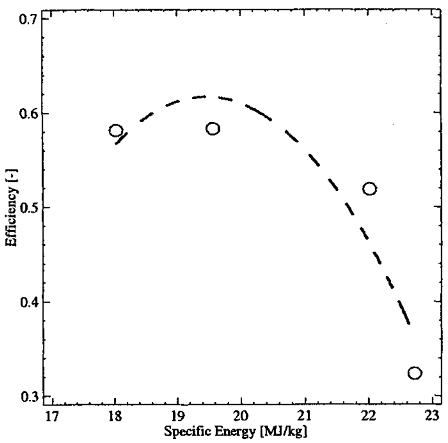

Fig. 14. Thrust efficiency of the helium arcjet with a current of 10.0A and various mass flow rates.

D. Non-intrusive diagnostics

Laser-induced fluorescence (LIF) is a technique employed in this lab to non-intrusively measure the temperature and velocity profiles of arcjets and Hall thrusters. Previous studies have measured the profiles of arcjets using hydrogen, helium, argon, and other propellants. The 728.1 nm transition (2^1P – 3^1S) was chosen as the transition to use for these measurements since it is well isolated from other transitions and accessible with the available lasers. A detailed description of the theory and setup can be found in reference [2].

Figure 15 shows the evolution of the lineshape as the anode voltage is increased. When little current is extracted from the arcjet, the lineshape is consistent with previous measurements. When the maximum current is extracted from the arcjet, the fluorescence signal is no longer present. Since this is a well-isolated transition, a thorough survey of wavelengths shows that the lineshape was nowhere to be found. To further investigate this of current was extracted from the arcjet plume (concomitant with little change on the velocity), at the maximum extracted current, the LIF signal could not be detected. A qualitative examination of the emission spectra confirms that the excited electronic states in the near exit plane region of the plasma plume were greatly perturbed and depopulated by the current draw. The only emission line that was distinctly visible was at 587 nm suggesting that there is energy pooling from nearby excited states into the upper level of this transition.

The next obvious step in the development of this hybrid thruster will be a small-scale demonstration. We have recently completed the fabrication of a helium arcjet that can operate with mass flow rates near 10 mg/s. The combination of this ultra-low power (<50W) arcjet and a low power (<500W) Hall thruster can be operated in our vacuum chambers.

ACKNOWLEDGEMENTS

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REFERENCES

1. Walker, Q.E., W.A. Hargus, Jr., and M.A. Cappelli, "Characterization of a Low-Power Helium Arcjet," AIAA-98-3636, 34th Joint Propulsion Conference, 1998.
2. Walker, Q.E. and M.A. Cappelli, "Laser-Induced Fluorescence Measurements of a Helium Arcjet Flow," AIAA-99-3603, 30th Plasmadynamics and Lasers Conference, 1999.
3. Scillinger, J., *Personal Communication*. 2000.
4. Cappelli, M.A., W.A. Hargus, Jr., and N.B. Meezan, "Coherent structures in crossed-field closed-drift Hall discharges," *IEEE Transactions on Plasma Science*, **27**(1): 96-7, 1999.
5. Chesta, E., N.B. Meezan, and M.A. Cappelli, "Stability of a magnetized Hall plasma discharge," *Journal of Applied Physics*, **89**(6): 3099-107, 2001.
6. Choueiri, E.Y., "Plasma oscillations in Hall thrusters," *Physics of Plasmas*, **8**(4): 1411-1426, 2001.
7. Haag, T. and F.W. Curran, "Arcjet Starting Reliability: A Multistart Test on Hydrogen/Nitrogen Mixtures," *Journal of Spacecraft and Rockets*, **29**: 444, 1992.
8. Storm, P.V. and M.A. Cappelli, "Laser-Induced Fluorescence Measurements Within An Arcjet Thruster Nozzle," AIAA-95-2381, 31st Joint Propulsion Conference, 1996.
9. Hargus, W.A., Jr. and M.A. Cappelli, "The structure of an expanding hydrogen arcjet plasma," *Physics of Plasmas*, **5**(12): 4488-4497, 1998.
10. Welle, R.P., et al., "One Kilowatt Hydrogen and Helium Arcjet Performance," The Aerospace Corporation, ATR-91(8443)-2, April 1993.