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Thruster Plume Plasma Diagnostics: A Ground Chamber Experiment for a 2-Kilowatt Arcjet

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Although detailed near field (0 to 3 cm) information regarding the exhaust plume of a two kilowatt arc jet is available (refs. 1 to 6), there is virtually little or no information (outside of theoretical extrapolations) available concerning the far field (2.6 to 6.1 m). Furthermore real information about the plasma at distances between (3 to 6 m) is of critical importance to high technology satellite companies in understanding the effect of arc jet plume exhausts on space based power systems. It is therefore of utmost importance that one understands the exact nature of the interaction between the arc jet plume, the spacecraft power system and the surrounding electrical plasma environment. A good first step in understanding the nature of the interactions lies in making the needed plume parameter measurements in the far field. All diagnostic measurements are performed inside a large vacuum system (12 m diameter by 18 m high) with a full scale arc jet and solar array panel in the required flight configuration geometry. Thus, necessary information regarding the plume plasma parameters in the far field is obtained. Measurements of the floating potential, the plasma potential, the electron temperature, number density, density distribution, debye length, and plasma frequency are obtained at various locations about the array (at vertical distances from the arc jet nozzle: 2.6, 2.7, 2.8, 3.2, 3.6, 4.0, 4.9, 5.0, 5.4, 5.75, and 6.14 m). Plasma diagnostic parameters are measured for both the floating and grounded configurations of the arc jet anode and array. Spectroscopic optical measurements are then acquired in close proximity to the nozzle, and contamination measurements are made in the vicinity of the array utilizing a mass spectrometer and two Quartz Crystal Microbalances (QCM's).

Introduction

The objective of the experiment is to obtain direct in-situ measurements of the arcjet exhaust plume characteristics by simulating the actual arcjet/solar array distance and geometry for satellites as they would be configured in orbit. Such plume characteristics are necessary to model the behavior of the solar panel immersed in the arcjet plume. Additionally, it was desired to determine whether tungsten ions from the arcjet cathode were present in any significant quantity in the arcjet plume. An attempt is made to detect the presence of tungsten ions using two QCM's, a mass spectrometer and optical spectroscopy techniques.

Experimental Setup

The arcjet experiment was performed in the B2 thermal chamber at the NASA Glenn Plum Brook Station located in Sandusky, Ohio. The B2 vacuum chamber is a world class facility (the largest facility of its kind in the world: 11.6 m diameter by 18.9 m high) capable of supporting full scale rocket engine thruster firings (sounding rockets, Delta III, and upper stage rockets such as the Centaur booster) all in a safe vacuum environment. Additionally the B2 facility is designed to handle cryogenic and storable rocket propellants, rocket exhaust products, test article emissions, and pressurant venting. A multitude of existing engine and chamber support systems (low-pressure vents, water cooled steam ejectors, etc.) can be employed to provide airflows, evacuate gases, and support a wide variety of test hardware. The B2 chamber has a sustained pumping speed of 330,000 liters per second (via ten large diffusion pumps) and is capable of extended testing for space simulation.

A spectrometer and photodiode detector array is positioned behind the quartz window on the outside of the chamber. A matched set of 45° UV enhanced elliptical mirrors are used to direct light from the arcjet plume onto a 50 micron entrance slit thereby filling the spectrometer with light. The arcjet is positioned on the triangular test stand in the center of the bottom end of the chamber. The solar array height is raised between two interchangeable positions 2.1 m (near) and 4.3 m (far) using an electric motorized winch. The 3 m diagonal probe diagnostic rake is directly mounted to the array at a fixed distance 8 cm above the array surface. Diagnostics consist of five 11 mm diameter gold plated stainless steel spherical Langmuir probes, two cylindrical wire probes (0.003 mm diameter tungsten), two DC emissive probes for measuring plasma potential, a single Faraday cup for measuring ion temperature and ion distribution and an anodized aluminum plate. The probes are evenly spaced along the diagnostic rake with the Faraday cup located towards the lower right end of the diagnostic rack. A single 1.9 cm spherical Langmuir probe and a wire probe is located in close proximity to the chamber wall (50 cm height above the test stand) to check that the arcjet plume density is sufficiently low at the chamber wall.

For the experiment a base pressure of 10^{-6} Torr was attained before allowing the simulated hydrazine gas mixture to flow. (Chamber pressure is monitored using gas manometers and ionization gauge.) The arcjet simulated gas mixture is made up of hydrogen, nitrogen and ammonia (in a 2:1:0.3 mole fraction), with flow rates of 2mg/s for H_2 and 40mg/s or N_2. A high impedance HV pulse is used to ignite the gas mixture flowing over the arcjet's electrically heated tungsten cathode.

Experimental Results

Initial pumping of the B2 chamber commenced on August 31, 2004. Twenty four hours latter hard vacuum was achieved. Background pressure was reduced to 9 µTorr over a 72 hour period. On November 8th the first successfully firing of the arcjet occurred. The arcjet remained operational for about seven hours. In the early morning of November 10th the arcjet was operational once again. The arcjet remained operational through November 22, 2004. With the arcjet operating the arcjet gas mixture (hydrogen and nitrogen) remained stable in the (380 to 420 µTorr range) (see fig. 1 for details).

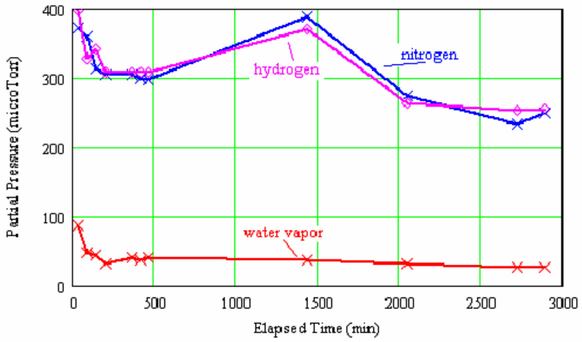

Figure 1.—A snapshot showing typical levels of residual gas with the arcjet operating on November 10, 2004.

The plasma parameters can be experimentally determined from the Langmuir probe volt/ampere characteristics or I-V curve. Typically the Langmuir probe is biased through a range of potentials (–30 to +30 V) and the current collected by the probe is measured with a very sensitive nano ammeter.

However the most commonly used methods for deducing the plasma parameters is not strictly applicable for this experiment because of the low density of the hydrogen plasma. In order to overcome the low hydrogen density problem a fitting formula with four adjustable parameters floating potential, (V_f), plasma potential (V_p), electron (T_e), and ion (T_i), temperatures) is used to circumnavigate the problem (fig. 2).

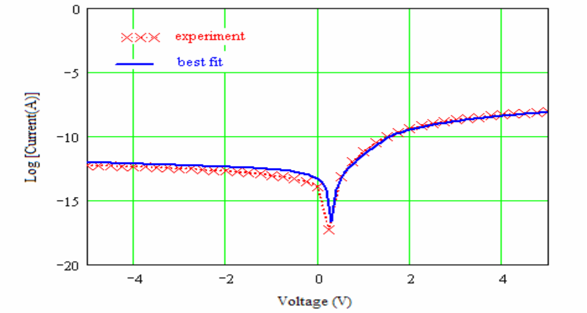

Figure 2.—Four adjustable parameters (V_f, V_p, Te, and N_i) are used to fit experimental points to theoretical calculations.

Both the cylindrical wire probe and the spherical Langmuir probe I-V characteristics were used to determine the plasma parameters. Additionally emissive probes were used to experimentally measure plasma potential values.

Attempts to measure electron number densities by exciting plasma waves (by arcing the anodized plate) and finding the peaks of the spectra resulted in the following data: $N_e = (10.4 \pm 11) \times 10^6$ cm^{-3} for wire probe number 1 and in $N_e = (11.7 \pm 6.3) \times 10^6$ cm^{-3} for Langmuir probe number 4, which despite the large error bars, are in general agreement with other measurements taken in the top position of the array. A simple plot of the density data is shown in figure 3. Because of changing experimental conditions (grounding and floating array, biasing individual strings, applying voltage between strings) and because of the natural errors in determination of the plasma number density much scatter is present in the density plots shown in figure 3.

An attempt to improve on the density measurements was made on November 18 by sweeping all Langmuir probes with both the arcjet anode and array at the floating potential. Figure 4 shows a plot of the November 18th measurements. The best fit of electron number density data (using 5 spherical Langmuir probes) is also given in figure 4. A plot of the plasma potential, floating potential and electron number density in the chamber is plotted in figure 5. Note that the plasma and floating potentials appear to follow one another closely in figure 5. The electron temperatures (fig. 5) range between 0.09 and 0.15 eV. The attempt to determine electron temperature from the recombinational continuum results in the following number: $T_e = 0.28(\pm 0.02)$ eV. Due to a bad connection in the Faraday cup wires no ion temperature and distribution data is available.

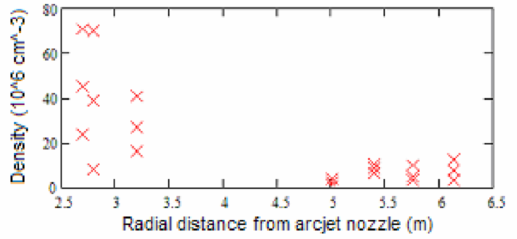

Figure 3.—Plot of density distribution data gathered between November 8–12, 2004.

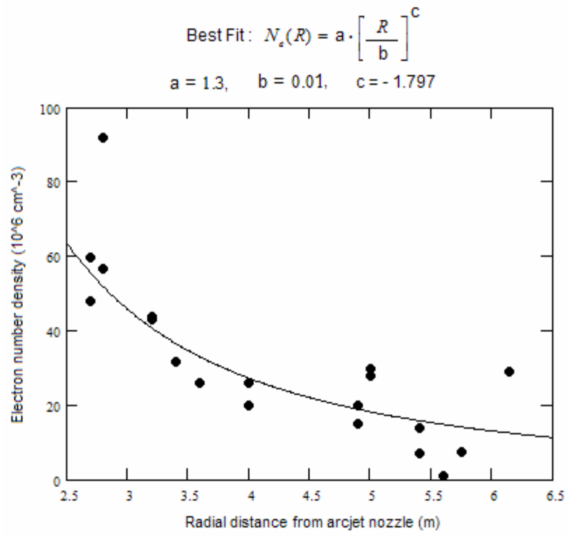

Figure 4.—Best data fit of number density taken November 18, 2004. The standard deviation, σ = 0.364.

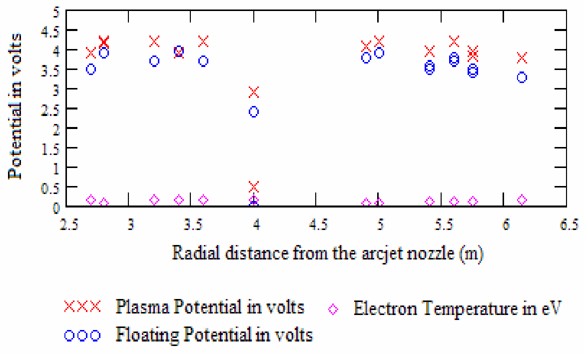

Figure 5.—Plots of electron temperature, plasma and floating potentials obtained November 18, 2004.

The QCM results showed little variation in either mass or frequency, all measurements lying well below the noise threshold of both detectors. As a result we were unable to confirm the presence of tungsten ions, a fact that was also born out by the mass spectrometer results. A finial attempt was made to confirm the presence of tungsten ions using the optical spectrometer with similar results. The entire optical spectrum was sweep (250 to 850 nm) with the central wavelength settings set in 50 nm increments. The optical spectrometer results are shown in figure 6.

Conclusions

Much important and valuable information about the arcjet plume is reported here. The plasma plume is characterized by low electron density (1.0×10^{7} cm^{-3} to 6.0×10^{7} cm^{-3}) cold plasma with electron temperatures ranging between 0.09 to 0.15 eV with mean value of 0.128 eV and a standard deviation, $\sigma = 0.026$. The plasma potentials for the most part ranged between 3.0 to 4.5 volts with floating potentials staying close ($\pm$0.5 V) to the plasma potential. The higher electron temperatures and number densities were found to be larger near the arcjet nozzle and smaller at the greater distances.

We were unable to detect the presence of tungsten ions (by a multitude of either QCM, mass or optical spectrometer measurements) However, an attempt was made to set an upper limit on the density of atomic tungsten. The most intensive spectral line of tungsten (λ = 400.88 nm in maximum transmission efficiency region of the photocathode detector) has an excited (ionized) state, T_e =3.4 eV, which corresponds to a transition probability equal to 1.63×10^{-7} s^{-1}. Comparing the ratio (of the product of transmission probability and line intensity of tungsten with the measured spectral intensity results for hydrogen) an upper limit on the number density of atomic tungsten is estimated at $N_W^* \leq 0.03 \cdot N_H^*$ cm^{-3}. Furthermore the distance an excited tungsten atom can travel is about three times shorter than for hydrogen. As a result if tungsten is ionized by thermionic electrons near the arcjet cathode the number of atoms of tungsten reaching a region where the spectrum is observable must be negligible.

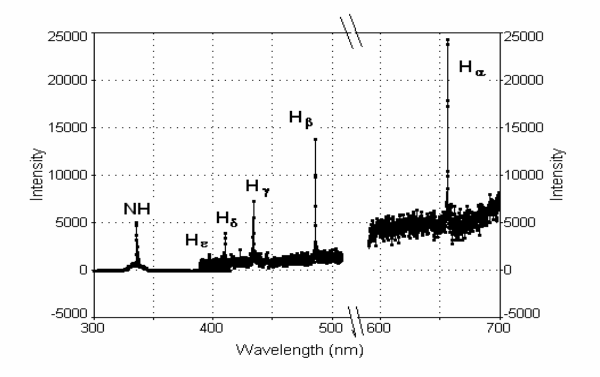

Figure 6.—The combined optical spectrum results in the range (250 to 800 nm).

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