Advanced Diagnostics of Arcjets

M.W. Crofton, R.P. Welle, S.W. Janson, and R.B. Cohen

The Aerospace Corporation
Los Angeles, CA 90009

Abstract

Advanced diagnostic techniques, especially those based on mass spectrometric and laser methods, are rapidly improving our understanding of arcjet performance on an atomic and molecular level. The new knowledge which is being acquired will aid efforts to develop accurate arcjet performance and contamination models and to improve arcjet efficiency. We focus on recent results obtained in our laboratory with advanced diagnostic methods. These results include measurements of velocity and density/flux distributions, and frozen flow losses associated with internal energy distributions. The current state of the techniques, relationships of results obtained by different methods (both standard and advanced) and their near future applications are discussed.

Introduction

Electric propulsion devices such as arcjets and ion engines are expected to play prominent roles in future low thrust/long lifetime applications for space systems.1–4 The increasing interest in electric propulsion derives from much higher specific impulses relative to chemical mono- and bi-propellant thrusters, coupled with technological advances in power subsystem capabilities5 and the ever-increasing importance and mission requirements of space systems. Typical geosynchronous satellite lifetimes can already be doubled through the use of arcjets and ion engines for stationkeeping, due to their high specific impulse ($I_p$). For orbital transfer applications, high $I_p$ allows the delivery of a high payload mass fraction from a 28.5° inclination low earth orbit to geosynchronous orbit. In this application, however, power levels greater than 25 kW are required to deliver a 2500 kg payload within 180 days. Any improvement in the energy efficiency of such devices significantly enhances capabilities and/or reduces system costs for a given mission.

Arcjets are electrothermal thrusters which utilize an electric arc to generate high propellant stagnation enthalpy. That enthalpy is converted to directed high specific impulse thrust through a nozzle expansion, with some additional arc heating occurring in both subsonic and supersonic flow regions. For monatomic propellants such as helium, neon, argon, etc., the high temperature plenum and plume contain atoms in various electronic states, plus ions and electrons. The distribution of excitation is highly nonthermal. For diatomic and polyatomic propellants, dissociation, as well as vibrational and rotational excitation, are also factors. The stagnation enthalpy is the sum of the random particle kinetic energies, plus the potential energies due to ionization, molecular dissociation, and the electronic, vibrational, and rotational energy distributions. Efficient transformation of stagnation enthalpy to directed kinetic energy in the expansion is the key to high thruster efficiency, and to widespread adoption for space applications. Energy remaining in the plume which does not appear as directed kinetic energy is referred to as frozen flow loss, and constitutes an important source of thruster inefficiency.

In order to improve arcjet energy efficiency, it is helpful to apply convenient diagnostic methods to quantify the relative contributions of all the various energy loss mechanisms. In this paper we will describe recent diagnostic measurements performed in our laboratory, and compare them with published results from other laboratories. We will focus on advanced mass spectrometric and optical diagnostic methods, and discuss their relation to standard diagnostic methods. The standard methods have been commonly used with arcjets starting in the 1960s.
Mass Spectrometric Diagnostics

A time-of-flight mass spectrometer (TOFMS) is an extremely powerful diagnostic for arcjets. Our TOFMS, also called a mass/velocity analyzer (MVA), has been described previously.\textsuperscript{6,7} It is capable of monitoring many masses simultaneously with resolution $m/\Delta m \sim 100$ and performing angle-resolved velocity measurements. For molecules and ions with translational energies $\sim 0.5$ eV and above, it determines kinetic energy distributions and flux levels by virtue of its position-sensitive detection TOFMS. In this case, a pulsed electric field accelerates all ions produced by an electron impact ionizer (or the thruster itself) toward a position-sensitive chevron microchannel plate (MCP) with 96 anodes in a linear array.

Because of their low mass, hydrogen atoms in arcjet plumes carry little kinetic energy, making a chopped-beam quadrupole configuration more desirable. In the chopped-beam technique, the time-of-flight of neutrals are measured across a fixed distance, yielding their velocity. The neutrals are ionized after they pass through the chopper and flight region, and mass filtered by the quadrupole. Even in this configuration, where only one mass can be monitored at a time, the centerline velocity distribution and angular flux can be determined for several species under multiple operating conditions in a single good day. Such distributions are shown in Figure 1 for $\text{H}_2$ and $\text{N}_2$ in the plume of a 590 W ammonia arcjet.\textsuperscript{8} By computing the quantity

$$\sum_i F_i = \sum_i m_i \langle v_{ax} \rangle_i$$

where $\langle v_{ax} \rangle_i$ is the expectation value of the axial velocity for the $i^{th}$ plume species, and $m$ is its mass, the total thrust can be determined. In the present example, the nitrogen generated 86 mN of thrust while the hydrogen molecules contributed 28 mN. Atomic hydrogen

Figure 1. For an ammonia arcjet operating at 590 watts, with 25 mg/s flow: top, $\text{H}_2$ speed distribution on axis; bottom, angular flux distribution of $\text{H}_2$. Top, $\text{N}_2$ speed distribution on axis; bottom, angular flux distribution of $\text{N}_2$. From Reference 8.
likely produces the next largest thrust contribution, but this is relatively minor, and the 114 mN deduced above agrees with thrust stand measurements to an accuracy largely related to the reproducibility and absolute accuracy of the ammonia flow meter. The specific impulse, thrust efficiency, and nozzle efficiency could all be accurately computed. A similar analysis was also performed for the case of pure H₂ propellant. The results are vastly superior to thrust stand measurements in that one can now observe in microscopic detail all contributions to the total thrust. This provides important new insight into thruster operation and greater possibilities for improved performance.

It is obvious from Figure 1 that the velocity distributions of N₂ and H₂ are quite different in the ammonia arcjet. The full-width-half-maximum (FWHM) is approximately twice as large for H₂, and the peak of the distribution is at 6.3 km/s versus 4.1 km/s for the nitrogen. This is a large amount of slippage, unknown for high pressure supersonic expansions without large internal energy sources. The translational “temperature” for the parallel (axial) component of the flow is calculated to be about 3500 K for N₂ and about 1000 K for H₂ on the basis of these distributions. Obviously the parallel translational “temperatures” for the two major components of the ammonia arcjet plume are widely divergent. This is not surprising for a mixture of light and heavy molecules, although the temperature slip, like the velocity slip, is very different from the value calculable for a similar expansion of H₂ and N₂ (P₀=1.5 atm, T₀=6000 K, d=0.625 mm, no energy source beyond nozzle entrance) from complicated semi-empirical relations.

A question of some importance concerns the rotational and vibrational temperatures of H₂ and N₂: will these also be widely divergent? The perpendicular translational temperature of the various components is more reflective of a thermal temperature; if these were measured, hydrogen and nitrogen values could conceivably be found to be in agreement. These issues are important for the basic understanding of the arcjet as a technical device, but especially important with reference to the arcjet efficiency and its possible improvement. Figure 2 shows the very significant effect upon thrust efficiency in the hydrogen arcjet, of 0.33 eV of internal energy per plume hydrogen molecule. The upper curve indicates the theoretical efficiency for an expansion to zero pressure with a 94% nozzle efficiency, 10% radiation loss, and molecular dissociation as the only frozen flow loss. In the arcjet, ionization, electronic and vibrational excitation, and possibly rotational excitation and extent of dissociation occur to a degree greater than predicted by the ideal model. Since the first excited vibrational level of H₂ occurs at 0.5 eV, less than one vibrational quantum per molecule on average is enough to make the arcjet rather inefficient. A greater degree of vibrational excitation is common in many discharges through hydrogen, since vibrational relaxation of hydrogen is notoriously inefficient. In practice, the only way to achieve certain knowledge on these, and many other molecular level issues concerning the arcjet, is to measure the individual parameters for each molecule. The use of optical diagnostic methods, a tool complementary to mass spectrometric studies, will be crucial for this task.

**Optical Diagnostics**

Optical diagnostics is perhaps the most powerful means of characterizing the arcjet and its performance. Optical diagnostic methods are unlikely to affect the property or phenomenon being measured, unlike many other approaches such as Langmuir probes, thermocouples, and even mass spectrometry. While the non-optical methods are very often useful in their own right, most of the definitive measurements are likely to be made by optical means, involving laser-based techniques. The laser has already been a revolutionary force in other areas of endeavor, including the similar field of combustion research. This is a result of the high intensity, narrow bandwidth, temporal and spatial resolution, among other properties, of lasers. Atomic and molecular densities, temperatures, velocities, electric fields - these can all be determined in the arcjet.
expansion by laser methods. (Unfortunately, the internals of the arcjet are less amenable to study.) Such measurements may be done point by point or by two-dimensional imaging.

Laser-induced-fluorescence (LIF) is the workhorse of laser diagnostic techniques, capable of routine detection of species present at low densities. While it is limited to atoms, small free radicals and several small stable molecules, these are the species that dominate arcjet plumes. While not as sensitive as LIF, nonlinear stimulated Raman techniques, such as Coherent Anti-Stokes Raman Scattering (CARS), have proven to be very useful in plasma environments and will probably be successfully applied to arcjets in the near future. Absorption techniques can generally produce the most accurate measurements, but suffer from low sensitivity. This is not a problem when the strongest electronic transitions can be utilized, but such transitions are often not conveniently accessible for small atoms and molecules.

Of course, optical emission spectroscopy has been a standard arcjet diagnostic for many years. It very quickly generates a great deal of qualitative information, concerning which excited state species are present and the various properties of the excited states. For example, rotational and vibrational temperatures have been determined for excited electronic states of NH and N₂. Electric field measurements have been made in the arcjet from high resolution emission spectra. The presence of electrode material in emission spectra can give qualitative clues concerning electrode erosion. With the advent of the optical multichannel analyzer (OMA), emission spectra with good spatial resolution can be acquired very quickly and conveniently. Unfortunately, the electronic excited states, with their relatively low populations and short lifetimes, are not representative of the bulk species population which accounts for the arcjet thrust and most of its properties. When coupled with the difficulties in quantifying most emission data, it is clear that optical emission spectroscopy is not usually the method of choice for most rigorous diagnostic measurements.

In a previous study, we obtained emission spectra with an OMA, as a function of distance downstream from the nozzle exit plane of an arcjet. The spectrum spanned the range from 300-700 nm, with observed transitions from all of the major atomic and molecular species in the plume, including the NH radical which accounted for a particularly intense band centered at 336 nm. Due to its intense emission, a large rotational constant which allows easy resolution of rotational band structure, and a convenient wavelength for spectroscopic observation, NH is a much-used emitter for diagnostic study of many systems, including flames, discharges, rocket plumes and astrophysical plasmas. The rotational and vibrational temperatures of the NH excited state A 3Π were determined and found to be 4300 K for rotation and 3700 K for vibration near the exit plane, with a decrease in vibrational temperature to 3100 K 12 mm downstream. The decay of NH emission was followed with axial distance, hence time, by the OMA, and the data are displayed in Figure 3 as contour plots. The A state lifetime is 0.4 μs for each rotational level involved, and the average axial flow velocity for NH is approximately 6 km/s. One would therefore expect an e⁻² reduction in emission intensity per centimeter of axial flow distance for unperturbed NH molecules in a collisionless flow. In fact, Figure 3 shows that it was observed to be less than an e⁻² reduction. The A state must therefore be repopulated by some mechanism, which will be discussed in connection with the LIF measurements.

To look for emission from more highly excited states, we recently surveyed the vacuum ultraviolet (vuv) region of the spectrum with a 1/4 meter vacuum monochromator and phototube in a photon counting configuration. For all practical purposes, the detector observes perpendicular emission from any species anywhere in the plume downstream of the exit plane, but no emission between throat and exit plane. Figure 4 compares the vuv emission from the arcjet and rf thruster. A qualitative difference is evident immediately: the rf thruster emits a larger flux of H₂ vuv radiation in spite of its lower operating power level, and the emission lines in the 150-170 Å region are broadened for the dc arcjet, indicating a much higher rotational temperature. The continuum region is enhanced for the rf thruster, a common phenomenon of high frequency discharges. The low photon flux observed across the entire spectrum indicates that radiative loss perpendicular to the plume is not a crucial energy loss mechanism for the dc arcjet. The Lyman-α transition at 121.5 nm, normally very intense in arc lamps and discharges in general, is observed only weakly in the dc arcjet and not at all in the rf thruster. The reason for the low intensity of Lyman-α seems to be revealed by the emission data from a helium Rydberg series in the dc arcjet (and rf as well) displayed in Figure 5. Each transition originates from an np 3P level and terminates on 2s 3S. The strongest member of the series in the figure originates from 5p (295 nm), and the weaker members come sequentially from n > 5.
The emission intensity of each transition can be related to a temperature $T$ and an average flow velocity $V$ from nozzle throat to exit plane using the relation

$$I = C f e^{-\frac{E/kT}{\tau}} e^{-(d/V)}$$

where $E$ is the energy of the upper state, $f$ is the atomic oscillator strength, $\tau$ is its radiative lifetime, $d$ is the distance from throat to exit plane, and $C$ is a normalizing constant. This relation is based on radiative emission decay with time, and equivalent collisional de-excitation cross sections for the various states involved in the series, and assumes that the stream velocity and temperature $T$ approach their terminal value in a distance $x << d$, so that $V$ and $T$ can be taken as constants with approximately terminal values. (The nozzle cone half-angle is 20°, the nozzle cone exit diameter is 9.4 mm, $d=12$ mm, and the throat diameter is 0.63 mm.) We have further assumed that decay of the upper states is much faster than their production between throat and exit plane for all but the first millimeter or two. Since the equation fits the observed intensities reasonably well (a similar fit was successful for the rf thruster), but fits poorly without the $e^{-(d/V)}$ factor, the data suggest that the Rydberg levels are not actively repopulated at reasonable distances beyond the throat and that properties such as velocity and temperature have approached their terminal values within just 5 throat diameters. These are powerful inferences derived from a rather simple experiment. Of course, not all atoms and molecules will necessarily follow this pattern, but the results to follow will support the notion that helium Rydberg levels are not alone in...
energy and velocity distributions, the molecule is excited to an upper electronic state with a laser pulse. Subsequent emission from the upper state is monitored, with intensities of individual transitions containing information concerning the ground state population distribution. The observed spectrum for part of the spectral region covered is presented in Figure 7 for the rf thruster and dc arcjet. Analysis of the data found the rotational temperature of ground state NH to be about 25 K in the rf thruster and 1600 K in the dc arcjet plume. The vibrational temperatures were 5000 and 2200 K, respectively. It is to be expected that collisional relaxation of H$_2$, N$_2$ and NH rotational states should be fast compared to vibrational or electronic collisional relaxation rates. As a result, rotational temperatures are often good approximations to local thermal temperatures even in highly non-equilibrium environments. This is obviously not the case for arcjet plume NH in the A state, but is quite possibly a fair approximation for the electronic ground state (recall that the A state rotational temperature was 4300 K vs 1600 K for the ground state). To lend credence to the latter notion, we would like to understand how the A state might be forced to acquire higher rotational and vibrational temperatures. The reaction

\[ \text{N}^2(\text{D}) + \text{H}_2 \rightarrow \text{NH} + \text{H} \]

may be the dominant mechanism for NH formation in the arcjet. For H$_2$ in the ground electronic state and v=0, NH is formed in v$\leq$3 in approximately equal amounts. Other formation mechanisms such as electron impact dissociation of NH$_3$ and NH$_2$, and electron recombination with NH$^+$, NH$^+_2$, and NH$^+_3$, may be important. Each of these mechanisms is likely to deposit considerable amounts of energy into rotation and vibration, resulting in highly non-Boltzmann distributions. Obviously, a large degree of NH X state rotational and vibrational relaxation has occurred in the arcjet by the time the molecule reaches the exit plane, 1.3 cm downstream of the throat. Some of the formation mechanisms alluded to may produce NH in the A state. The same opportunity exists there for rotational and vibrational relaxation, yet we find distributions which are much more hot. Electron impact excitation of NH to the A state is unlikely to occur in the relatively field free region beyond the exit plane where NH densities have decreased precipitously and NH formation rates have also been reduced by orders of magnitude.

The observed NH A state emission could be due to reabsorption of the intense radiation emitted by highly excited NH molecules in or near the throat. If 1 to 10% of the NH$_3$ molecules flowing into the arcjet give rise to an NH molecule which undergoes an A→X transition, our calculations suggest that ground state NH

![Figure 5](image_url)

Figure 5. Helium Rydberg series emission spectrum, corrected for phototube response, and calculated intensity using the equation shown.

![Figure 6](image_url)

Figure 6. Schematic of experimental setup for LIF studies. NB=narrowband, PMT=photomultiplier tube. The slit improves spatial resolution. The chamber optics, arcjet and motorized XY stage are supported by the platform.

this respect. Finally, it is interesting to note that the rate of emission decay with distance could be used to perform useful routine measurements of stream velocity with very inexpensive apparatus.

An experimental schematic diagram for our application of LIF to the study of NH in the arcjet plume is given in Figure 6. Details have been given previously. To determine ground state vibrational and rotational
Figure 7. Comparison of NH LIF spectrum for rf thruster and dc arcjet, showing a dramatic difference.

molecules beyond the exit plane will have a significant reabsorption probability which will increase the A state rotational temperature. From the 400 ns lifetime of A\(^3\)Π NH,\(^{26}\) and the 6 km/s mean exit velocity also determined by LIF (see Figure 8), the probability that NH, created in the A state near the throat, emits within one lifetime period after crossing the exit plane, is on the same order as the probability of ground state reabsorption of A→X background radiation. This mechanism for formation of the NH A state in the plume could also account for the significant difference between the

Figure 8. Inferred NH velocity distribution about 1 inch beyond exit plane. The two peaks correspond to red and blue Doppler shifts for a single transition, since the laser beam crosses the plume at 31 degrees off perpendicular and is reflected upon itself. The peak on the left is weak due to thruster-induced degradation of the reflector. The x-axis indicates velocity with respect to the axial projection of the laser direction of propagation.

A state vibrational and rotational temperatures, the apparent non-Boltzmann distribution of A state rotation, and the unusual circumstance that rotational temperature is much higher than vibrational temperature. Since the selection rules limit the rotational portion of an electronic transition to \(\Delta J=0,\pm 1\), when light is first emitted by excited NH molecules in the arc region, absorbed by ground state NH molecules in the plume, and subsequently re-emitted to the detector, an apparent temperature will result which is a convolution of the NH A state temperature in the arc and the NH X state temperature in the plume. The signal strength at high J numbers would be due to the relative lack of population at those J levels in the NH X state in the plume; photons arising from transitions between levels with very high J numbers in the arc will be reabsorbed at a relatively low rate. Since the Franck-Condon factors are near zero for any transitions involving a change in vibrational level, the NH A \(v=1(0)\) state could be repopulated through absorption in the plume only from the NH X \(v=1(0)\) state. The vibrational temperature of the upper and lower states should therefore be similar, as observed. These factors account for the high A state rotational temperature and the much lower vibrational temperature, since the collisional quenching rate\(^{27}\) is slower than radiative relaxation beyond the exit plane.

As a result of repopulation by the reabsorption of
background radiation, the intensity of A→X emission would fall at a rate slower than indicated by the factor \( \exp(-At/400 \text{ ns}) \), which in fact was observed and already discussed in relation to Figure 3. That the NH total concentration falls according to \( 1/r^2 \), where \( r \) is the axial distance beyond the throat, was verified by LIF intensity measurements as a function of \( r \) (see Figure 9). Due to the effective spatial resolution of the LIF measurement of several millimeters, the signal deviates from a \( 1/r^2 \) relation near the exit plane. Any of the other possible mechanisms for repopulation of the A state which involve a net NH production - most were mentioned above - will lead to an NH density which decreases less rapidly than \( 1/r^2 \). This is definitely not the case more than one inch beyond the exit plane. Additional support for the reabsorption hypothesis is provided by the observation that radiation trapping occurred when a grouping of the strongest Q branch transitions was monitored by LIF; the effect was able to increase the apparent fluorescence lifetime to 1.0 \( \mu \text{s} \), indicating also that NH constitutes more than 1% of the total number of plume atoms and molecules. Finally, another arcjet emission study found a rotational temperature for NH C \(^1\)II of 2500 K.  

The state dependence of the rotational temperature of NH is especially significant in view of the fact that extrapolation of the rotational temperature of small electronically excited molecules in arcjet plumes and other plasmas to bulk temperature has been quite commonly done. Extrapolation using electronically excited molecules to bulk properties should be practiced only with extreme caution and careful analysis; in the case of NH, the extrapolation would lead to a very erroneous result. Other properties of excited states, including velocity distributions, may also lead to erroneous results if extrapolated.

If the rotational degree of freedom for all long-lived electronic states of plume molecules is near equilibrium, then we expect ground state N\(_2\) and H\(_2\) to have a rotational temperature in the vicinity of 1600 K. We have previously mentioned the divergent parallel translational temperatures of N\(_2\) and H\(_2\), and we also note that the rotational temperature of N\(_2\) in the C \(^3\)II\(_g\) electronically excited state has been determined by emission spectroscopy to be about 800 K. While such temperatures do not directly contradict the equilibrium hypothesis, they do suggest the need for caution. Equilibrium assumptions should be tested experimentally. A partial test was conducted by measuring the perpendicular velocity distribution of ground state NH. The translational temperature which we derived from a single Gaussian fit was approximately equal to the rotational temperature.

With our present knowledge concerning rotational and vibrational temperatures in the ammonia arcjet, it is nearly certain that rotational plume energy is a minor contributor to the arcjet inefficiency; we have previously estimated that it carries away about 5% of the total non-thrust power (3.5% of total input power).

We have indirectly determined that the largest losses in the ammonia arcjet are due to thermal radiation from the body of the arcjet and dissociation of NH\(_3\) to N\(_2\) and H\(_2\) followed by dissociation of H\(_2\). For the hydrogen arcjet, where the average translational energy per molecule is several times lower, the relative contributions of vibration and dissociation could be quite different.

Concluding Remarks

Measurements of macroscopic quantities such as thrust, contamination potential, temperature, and electromagnetic emission/interference, can be understood by molecular level measurements. The most dramatic example is the accurate calculation of total thrust by the integration of the flux-velocity product as a function of angle for H\(_2\) and N\(_2\) in the plume of an ammonia arcjet.
Current laser-based diagnostic methods often involve a considerable amount of effort per measurement. Several of the most important plume species – \( \text{H}_2 \), \( \text{N}_2 \), and \( \text{H} \) – are not amenable to ground state study, since strong electronic transitions from the ground state only exist at photon energies above 10 eV. Nonlinear approaches may require complicated analysis. The advantage of laser-based methods is that the measurements are usually precise and nonintrusive. Technological improvements and the incorporation of imaging techniques such as two-dimensional LIF will allow the generation of high quality data more efficiently.

There are several measurements of fundamental importance yet to be done and related to arcjet energy inefficiency, and they seem to require lasers. One is the \( \text{H} : \text{H}_2 \) ratio in hydrogen and ammonia arcjets, another the internal energy distribution in the \( \text{H}_2 \), especially regarding vibration if the propellant is pure hydrogen. Concerning lifetime considerations, LIF monitoring of eroded electrode and other materials in real time will be an essential measurement. Mass spectrometry, of course, is another attractive way to study erosion processes.

Because the application of advanced diagnostics to arcjet thrusters is still at an early stage, the relationships of some of the measurements made by various methods are not clearly understood. We have already discussed the uncertainty in relating MVA velocity distribution measurements, \( \text{N}_2 \) rotational temperatures of excited states determined by emission spectroscopy, and rotational and translational temperatures determined for \( \text{NH} \) by LIF.

The quantity of available molecular-level diagnostic data for arcjets is increasing rapidly. The data is already providing useful indications concerning energy loss mechanisms. The gray body radiative and dissociative mechanisms appear to produce the greatest losses, at least in the 1 kW ammonia arcjet. A complete picture concerning energy loss in ammonia and hydrogen arcjets is expected to emerge soon.

Of course, it is not enough to quantify erosion processes in real time and energy loss for each molecular-level category. The techniques must also be exercised over arcjet "design space," and accurate performance and contamination models need to be developed to generate optimized thrusters. Regenerative cooling will reduce the thermal losses to more acceptable levels. Dissociation could be reduced if the arc did not pass through the nozzle and attach outside, although this may not be achievable without unacceptable arc instability. Many smaller design changes may prove to be beneficial as well. To be truly useful, several diagnostic measurements should be performed at once on a given thruster which undergoes design perturbations. Diagnostics development has proceeded to a point where this is easily imaginable in the near future.

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**References**


