EMISSION SPECTROSCOPY OF 1 kWe ARCJET OPERATING WITH SIMULATED HYDRAZINE

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Abstract

Low power radiatively-cooled arcjet thrusters are being developed at BPD Difesa e Spazio under ESA sponsorship. Test facilities and diagnostics were set-up which included an emission spectroscopy system. The emission spectroscopy system enables a detailed characterization of the thruster through analysis of the exhaust plume. This paper describes the application of emission spectroscopy to the plume of a low power arcjet operating at 1 kWe using a mass flow rate of 50 mg/s of a nitrogen-hydrogen mixture to simulate hydrazine. The profiles of the emitted hydrogen Balmer-3 line are compared with gaussian and lorentzian profiles in order to investigate the contributions of Doppler and Stark broadening. The contributions are studied as functions of the distance from the nozzle exit and vertical displacement about the thruster axis. An electron density of $10^{14}$ cm$^{-3}$ was found through Stark broadening in the region of the nozzle exit. Centerline axial velocities were measured on the engine axis as function of the distance from the nozzle exit for both nitrogen and hydrogen. A centerline axial velocity of 2.5 km/s was found for hydrogen 5 mm downstream of the nozzle exit. The centerline axial velocity exhibited by nitrogen was lower than the hydrogen axial velocity but the magnitudes of the velocities for these species are closer than what was expected. This is believed to result from the redistribution of velocities as a consequence of collisions between plume species and vacuum chamber background gases.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
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<tr>
<td>BPD</td>
<td>BPD Difesa e Spazio</td>
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<tr>
<td>NSSK</td>
<td>North-South-Station-Keeping</td>
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<tr>
<td>MNH</td>
<td>Mono-Methyl Hydrazine</td>
</tr>
<tr>
<td>N$_2$H$_4$</td>
<td>anhydrous hydrazine</td>
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<tr>
<td>TZM</td>
<td>alloy of Molybdenum (99.4%), Zirconium (0.08%), Titanium (0.5%)</td>
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<tr>
<td>IS</td>
<td>specific impulse</td>
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<tr>
<td>LIF</td>
<td>Laser Induced Fluorescence</td>
</tr>
<tr>
<td>FWHM$_c$</td>
<td>Doppler Full Width Half Maximum</td>
</tr>
<tr>
<td>FWHM$_s$</td>
<td>Stark Full Width Half Maximum</td>
</tr>
<tr>
<td>c</td>
<td>velocity of light, 3.0 $10^8$ m/s</td>
</tr>
<tr>
<td>k</td>
<td>Boltzmann's constant, 1.380 $10^{-23}$ J/K</td>
</tr>
<tr>
<td>l', l&quot;</td>
<td>line profile</td>
</tr>
<tr>
<td>M</td>
<td>species mass (AMU)</td>
</tr>
<tr>
<td>mk</td>
<td>wave number in cm$^{-1}$ divided by 1,000</td>
</tr>
<tr>
<td>N$_e$</td>
<td>electron density (cm$^{-3}$)</td>
</tr>
<tr>
<td>n</td>
<td>principal quantum number (n = 1, 2, 3,...)</td>
</tr>
<tr>
<td>e</td>
<td>Neper's number (2.718)</td>
</tr>
<tr>
<td>T</td>
<td>temperature (K)</td>
</tr>
<tr>
<td>V$_0$</td>
<td>velocity component along the direction of observation</td>
</tr>
<tr>
<td>V$_z$</td>
<td>velocity axial component</td>
</tr>
<tr>
<td>V$_{xz}$</td>
<td>velocity component on the horizontal plane</td>
</tr>
<tr>
<td>v</td>
<td>spectral frequency, wave number (cm$^{-1}$)</td>
</tr>
<tr>
<td>$\nu_0$</td>
<td>wave number of the line peak</td>
</tr>
<tr>
<td>$\Delta \nu$</td>
<td>frequency Doppler shift</td>
</tr>
<tr>
<td>Z</td>
<td>spacial integral of the transition total intensity (on the half plume section)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>angle of V$_{xz}$ with respect thruster axis</td>
</tr>
<tr>
<td>$\alpha_{1/2}$</td>
<td>reduced wavelength distance (Ref. 25)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>observation angle with respect thruster axis</td>
</tr>
<tr>
<td>$\tau$</td>
<td>decay time of the transition (s)</td>
</tr>
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</table>

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Introduction

Low power arcjet systems are compatible with current on-board satellite power levels and propellants such as hydrazine and ammonia. The use of hydrazine is particularly significant since many existing and planned satellites use this propellant for most propulsion functions and hydrazine arcjets are compatible with the dual mode propulsion system concept\(^\text{Ref. 1}\). Arcjet engines offer specific impulse values of 400 s to 600 s using hydrazine while operating at power levels of 1 kW to 2 kW. A comparison of specific impulses provided by propulsion options currently used for NSSK\(^\text{Ref. 2}\), namely: monopropellant \( \text{N}_2\text{H}_4 \) chemical thrusters \( (I_\text{sp} = 220 \text{ s}) \), bipropellant MNH/\( \text{N}_2\text{H}_4 \) chemical thrusters \( (I_\text{sp} = 285 \text{ s}) \) and hydrazine resistojets \( (I_\text{sp} = 302 \text{ s}) \), shows a greater advantage for the arcjet. The conclusion reached through this comparison is that arcjet thrusters will have a major impact on reducing propellant mass and increasing the economic return on investment for many commercial satellite systems. The advent of the usage of arcjet propulsion subsystems within dual mode satellite propulsion system for NSSK in the USA\(^\text{Refs. 2, 3}\) has demonstrated the acceptance of this technology for commercial applications.

Even though arcjets have been accepted for flight applications, efforts are continuing to improve thruster performance at several laboratories. Present arcjet engines convert the input electrical power into thrust with efficiencies of only 25% to 35%. Most of the energy loss is unrecovered power deposited in the propellant. Minimization of these losses requires a better understanding of plasma processes during arcjet operation. Optical diagnostic techniques can be used to obtain this knowledge since they do not perturb the flow. The first optical diagnostic applied to arcjet plumes was emission spectroscopy\(^\text{Ref. 4}\). Over the last several years, other optical diagnostics have also been applied since each technique can provide specific types of information. LIF has been employed for spatially resolved measurements of the exit vector velocities, Doppler widths and densities of hydrogen species\(^\text{Refs. 5 - 7}\) and rotational and vibrational temperatures of NH in its ground electronic state\(^\text{Ref. 8}\). Raman scattering has been applied to determine the molecular ground state population and temperature of \( \text{H}_2 \)\(^\text{Ref. 9}\), while vacuum ultraviolet absorption has been used to determine the atomic ground state population and temperature of hydrogen\(^\text{Ref. 10}\). Finally, emission spectroscopy, even though it does not allow for spatially resolved measurements, is a technique which can provide excited state populations and temperatures and electron densities. Emission spectroscopy in the visible range has been used for NH species\(^\text{Ref. 11}\), while emission spectroscopy in the ultraviolet range has been applied to investigate nitrogen and hydrogen species\(^\text{Ref. 12}\). Emission spectroscopy measurements have been performed mainly on arcjets operating on hydrogen with only a few exceptions concerning arcjets operating on ammonia\(^\text{Refs. 6, 12, 13}\) or on a nitrogen-hydrogen mixture simulating hydrazine\(^\text{Refs. 14, 15}\). It is desirable that, as is ongoing for hydrogen arcjets, efforts are made to obtain a data-base concerning plasma properties for engines operating on simulated hydrazine and on hydrazine. These data-bases are important to aid in arcjet design aimed towards more efficient engine configurations and for numerical modelling of these types of arcjets.

Development of low power arcjets is presently ongoing at BPD under ESA sponsorship within a program which includes both medium and low power arcjet development. The test activities include parametric mapping using nitrogen, hydrogen, ammonia and nitrogen-hydrogen mixture simulating hydrazine\(^\text{Refs. 16, 17}\), parametric characterization with catalytically decomposed hydrazine\(^\text{Ref. 18}\) and endurance testing\(^\text{Ref. 19}\). The ESA arcjet program goals also include plume characterizations using emission spectroscopy. Medium power arcjet plume investigations have been reported earlier\(^\text{Refs. 20, 21}\).

This paper presents the results of the plume analysis performed during low power arcjet operation with simulated hydrazine. In particular, the emission spectroscopy system operating at BPD allows for spacial scans of the jet along the thruster axis, perpendicular to this axis and for different angles of observation with respect to the thruster axis. The characterization of the exhaust includes species identification, line profile analysis and measurements of the centerline axial velocity component for hydrogen and for nitrogen species. The measurement of the centerline axial velocity component immediately at the nozzle exit is compared to the specific impulse inferred through thrust and propellant mass flow rate measurements.
This analysis will be repeated in the future on the plume of the thruster while operating on catalytically decomposed hydrazine and will allow a better comparison between performance exhibited with the two propellants. Data inferred from the frequency analysis of the hydrogen Balmer-8 line profiles, as integrated along the line-of-sight of the optical system, are presented for different vertical and axial positions with an observation angle perpendicular to the thruster axis. The theoretical lorentzian and gaussian fits for these Balmer-8 line profiles are shown for different thruster centerline positions as well as for positions below the thruster axis. The Balmer-8 line-widths, as a function of the distance from the nozzle exit and the vertical displacement about the thruster axis, are included and the electron density inferred through these line widths is presented. Line profiles are shown which were measured at angles of observation different from 90° with respect to the thruster axis, so that the axial velocity component could be inferred.

**Experimental Apparatus**

The MOD-B arcjet, test facilities and emission spectroscopy system are reviewed in this section.

**MOD-B Arcjet Engine Design**

The thruster used for the tests described in this paper is a 1 kW radiatively-cooled arcjet, denoted MOD-B, and is shown in Fig. 1. A detailed description of the this thruster can be found elsewhere\(^{(Ref. 16 - 19)}\) and is summarized below. The MOD-B configuration used during the tests includes a 2% thoriated tungsten nozzle insert with a 0.71 mm diameter and a 0.69 mm long constrictor. The conical nozzle has a 20° half angle and an area ratio of 32. The propellant is tangentially injected into the plenum chamber through four 0.5 mm-diameter injectors, each with a semicircular cross-section. The injectors are milled into a molybdenum insert. The cathode is a 3 mm diameter, 2% thoriated tungsten rod with a 15 mm-long, 2 mm-diameter front section. The cathode ends with a conical tip which has an included angle of 60° and a tip radius of 0.3 mm. The cathode is inserted through the rear of the engine and held by a swagelock connector. The electrode gap was set at 0.4 mm. To eliminate potential problems from the unequal thermal expansion of different materials within the engine, a stainless steel spacer ring is placed within the rear assembly nut to maintain the sealing pressure at the graphite gasket. The compression spring compensates for the different thermal expansions between the boron nitride insulator and the TZM outer engine body and insures continuous contact between the insulator, gas injection insert and anode piece. The nitrogen-hydrogen mixture (simulated hydrazine) was injected near the rear of the engine to provide some regenerative cooling of the engine and pre-heating of the propellant.

**Test Facilities**

The low power arcjet was tested in a completely automated facility which is provided with an optical diagnostic system. This facility, VP-1, is the largest of the two test facilities\(^{(Ref. 22)}\) used for arcjet development at BPD and consists of a water-cooled vacuum tank 1.6 m in diameter and 4.0 m in length. The tank is evacuated by a four-stage pumping system with a total pumping speed of 58,000 m\(^3\) per hour. The tank pressure was maintained at approximately \(10^{-2}\) mbar during the tests. Aside from the optical system, diagnostic instrumentation included a thrust stand developed for low thrust measurements\(^{(Ref. 16 - 19)}\), voltage and current probes, mass flow meters, pressure transducers and a video camera.

The electrical power supply\(^{(Ref. 19)}\) was composed of a main power supply and a start-up device connected in parallel. The start-up device was composed of a high voltage/low current power supply unit, a 5 \(\mu\)F capacitor bank, a diode block and a 1.4 \(\mu\)H inductor. The matching of the electrical characteristic of the main power supply and the engine was accomplished by a 0 to 11 Ohm manually-set, variable ballast resistor in series with the engine. The variable ballast resistor was also used to reduce the current spike during the capacitor bank discharge and to compensate for the main power supply ramp-up time.

The arcjet is mounted on the thrust stand to monitor engine performance during operation. In
order to avoid thermal drift in the thrust measurement, the engine is fixed to the thrust stand through insulating connectors and the critical parts of the thrust stand are enclosed in a water-cooled shield to minimize radiation and hot gas impingement.

Optical System Design

An emission spectroscopy system has been designed to determine plasma properties such as velocity, relative species concentrations and the temperature of the excited atomic and ionic species existing in an arcjet exhaust plume. The system is shown schematically in Fig. 2 and is briefly described below since it was presented in detail in papers at previous Electric Propulsion Conferences. (Refs. 20, 21) The whole system is located outside and immediately adjacent to the vacuum chamber where the thruster is tested. Windows equipped with tempered glass, that enables only transmission of wavelengths within the visible range, allow optical access to the plasmajet.

Light coming from the plasma plume is deflected by a flat mirror and collected by a two lens telescope system with an adjustable focus. These optical elements are mounted on a translating carriage which moves along a rail parallel to the thruster axis and enables the distance from the nozzle exit to be varied. The angle of the flat mirror (with respect to the thruster axis) can be varied through a rotation stage. This rotation movement, together with translation, allows variation of the plume observation angle. The collimated light beam generated by the telescope is deflected vertically towards the optical bench by means of a 45° flat mirror fixed on the rail which supports the translating carriage. The rail can be translated vertically allowing the plasma volume under analysis to be obtained above or below the thruster centerline. A 45° flat mirror fixed to the optical bench deflects the light beam towards a biconvex lens that focuses the beam (deflected by means an other 45° flat mirror) on the entrance slit of the spectrometer. The order-sorter placed at the entrance slit of the spectrometer during the previous study (Ref. 21) has been removed since the spectral range used during the present analysis did not exhibit superposition of spectral lines. The order sorter has been replaced with a 45° flat mirror which improved the transmissivity of the total system by approximately 50%.

The spectrometer is a SOPRA DMDP2000 and uses two grating monochromators completely equal working in tandem. Both have a 2 m focal length with a Fastie-Ebert mounting. The maximum resolution of the spectrometer is 0.03 cm⁻¹ at a frequency of 15,000 cm⁻¹ when it is used in double-pass configuration. In this case, the incoming ray is diffracted twice on each grating allowing for an increase in the resolution by a factor 1/2, with respect that reached through a single-pass configuration. A frequency repeatability of ± 0.004 cm⁻¹ (within 10 cm⁻¹ range) is possible when a thermaling system keeps the temperature of the instrument stable to within ± 0.2 °C. The measurements described in this paper were done in single pass configuration with a corresponding resolution of about 0.04 cm⁻¹.

A side-on HAMAMATSU photomultiplier tube with a spectral response range of 85 - 930 nm is mounted on the exit slit of the spectrometer and is provided with a Peltier effect-cooled housing to reduce dark-counts to less than 20 counts per second.

Finally, the mechanical movements of the collection optics, the spectrometer's slits and those with which the spectrometer performs frequency scans, are completely motorized and managed by a personal computer. Data acquisition software has been developed to allow fast frequency recalibration and sequential frequency scans of plasma volumes within defined boundaries of the plume regions to be analyzed.

Test Conditions and Procedures

The thruster operating conditions and measured performance for the presented results are summarized in Table 1. The variations indicated for the reported quantities are due to the fact that during the spectroscopic analysis, the thruster exhibited performance variations at constant power.
During thruster operation, raw data were taken through emission spectroscopy as described below. A wide frequency scan over the range from 15,200 cm$^{-1}$ to 20,600 cm$^{-1}$ was performed in order to determine the main species existing in the plume and to select some spectral lines suitable for velocity measurements. This frequency range was chosen since spectral lines emitted by N$_2$, Ni and H were expected. The scan over this frequency range was performed with a slit width of 30 μm and a frequency step of 100 mk. After recognition of the emitting species, two spectral lines were selected for analysis; one for hydrogen and the other for nitrogen. For hydrogen, the Balmer-β was chosen since this spectral line is characterized by a higher susceptibility to Stark broadening than the Balmer-α line. This could allow an easier theoretical fit through a lorentzian shape which is impossible when the Stark and the Doppler effects are comparable. The Balmer-β line was used to study the intensity distribution in the plume and along the thruster axis in order to define the spacial limits for a suitable spectral analysis. As a result, a spectral analysis over a frequency range centered at 20,565 cm$^{-1}$ was performed. The scan was particularly wide, typically 23 cm$^{-1}$, due to the large wings characterizing the lorentzian profile of this spectral line. During this analysis, the frequency step was reduced to 30 mk and a photon counting time of 1 s was set. The frequency scan over the selected range was repeated at several vertical positions along a plume section perpendicular to the thruster axis, ranging from the engine centerline to 8 mm below it with a spacial step of 2 mm. The vertical scans were performed at distances of 2 mm, 5 mm, and 8 mm downstream of the nozzle exit. The measured spacial resolution was 2 mm along the thruster axis and 30 μm in the direction perpendicular to this axis. Frequency scans, at a right angle with respect to the thruster axis, were used for line intensity and line width measurements. For the analysis of the nitrogen species existing in the plume of the MOD-B engine, the spectral analysis was performed over a frequency range, typically 6 cm$^{-1}$ wide, centered at the frequency 20,279 cm$^{-1}$. The slit width, frequency step and photon counting time were the same used for the analysis on hydrogen.

In order to measure the axial velocity, frequency scans were performed using two different, non perpendicular viewing angles 108° and 50°, along the thruster centerline with respect to the thruster axis. In order to detect a line shift as large as possible along both viewing angles, the two directions of observation were selected to maximize the viewing angle with respect to the perpendicular to the thruster centerline. The selected angles are the maximum and the minimum, respectively, allowed by the actual position of the thruster with respect the frame of the windows used for the plume analysis and a water-cooled radiation shield mounted on the thrust balance. Symmetrical viewing angles are preferable since they allow for monitoring of the symmetry of the plume with respect to the vertical plane on the thruster centerline, but were not used since the maximum angles provided better axial velocity resolution.

The general procedures used to conduct emission spectroscopy consist of: resetting of the spectrometer frequency counter, raw data collection and line profile reconstruction. Resetting of the spectrometer frequency counter is performed by moving the gratings for the frequency scan, until they are in transmission on the peak of a spectral line included in the calibration curve which is chosen as the reference line. The raw data is collected as described above.

Line profile reconstruction is obtained by means of noise and background signal subtraction and the fit with a theoretical shape. The main parameters of the emitted spectral line are obtained from this fitted profile when the chi-square value is very close to 1. If this condition is not fulfilled, the parameters of the spectral line are obtained through the raw data directly. These parameters are the total intensity, the peak frequency and the intrinsic FWHM. The intrinsic FWHM is the detected line width corrected for the instrument broadening. The peak frequency of an unknown spectral line can then be determined with an error smaller than the instrument resolution if the spectrometer frequency repeatability is good. This is true if two conditions are fulfilled: a) the temperature of spectrometer is kept stable to within ± 0.2 °C and b) the calibration curve includes a spectral line that is in transmission through the spectrometer at an angle of incidence on the grating very close to the angle at which the unknown spectral line is transmitted. In the case of
Doppler shift measurements, is preferable to include the unshifted line in the calibration, but is not strictly required.

Doppler shift measurements were made on the thruster centerline. The peak frequency of the spectral line detected at an observation angle of 90° with respect to the thruster axis, was used as the unshifted reference line. This unshifted reference line was selected instead of the unshifted spectral lines emitted by nitrogen and hydrogen spectral lamps since the differences found between the peak frequency of the two unshifted lines was within 0.01 cm⁻¹. The repeatability of the spectrometer during the tests was also checked. For this purpose, the peak positions of the Balmer-β line from an hydrogen spectral lamp, before and after the tests, were compared. Finally, in order to subtract the instrument broadening from the measured line widths, the resolution of the spectrometer was measured in the data collection configuration with the vacuum pumping system on immediately before each test run. The spectrometer resolution was also checked at the end of the test run to check for any degradation during the test. A mercury spectral lamp was used for this purpose. In particular, the spectral line at 22,938 cm⁻¹ was used, the intrinsic line width of which was measured at the high resolution facility of the University of Rome.

Theoretical Considerations

The study of the spectrum emitted by an arcjet plume can provide information on plume parameters such as the species present, their temperature and velocity distributions and the ionization fraction. An extensive theory which relates plasma parameters with characteristics of the emitted spectrum is available in literature\(^{23 - 25}\) and is briefly summarized in this section with particular emphasis on the line broadening mechanisms and Doppler shift effect which have been applied to elaborate the raw data.

Line Profiles

It has been recognized for a long time that the shape of a spectral line is a complicated function of the environment of the radiating molecules, atoms or ions, and depends notably on pressure and temperature. The analysis of line profiles combined with an adequate theory represents therefore an attractive noninterfering probe for the diagnostics of the plume. A spectral line emitted by a radiating source, like the plume, is characterized by a shape which is determined by several general mechanisms each of which generates a typical frequency distribution. The main parameters of the frequency distribution are the shape and the line width. The most important of the general mechanisms are: 1) the instrument effect, which in the case of the spectrometer used for reported results generates a gaussian profile, and its corresponding characteristic width called instrumental broadening; 2) the thermal Doppler effect, which generates a gaussian profile and whose characteristic width is related to temperature of the radiating species; 3) the Stark effect due, in general, to the interaction of the emitting source with charged particles (ions and/or electrons) which generates a lorentzian profile (for the case of electrons acting as the perturbing system, the characteristic lorentzian width is related mainly to the electron number density, and with less sensitivity, to the electron temperature) and; 4) turbulence and/or unresolved macroscopic motion of the radiating species, which in some cases also results in gaussian profiles of which the characteristic width is related to the relative macroscopic velocity component along the line-of-sight of the various volume elements of the emitting source. All these effects compete and in some cases one will prevail over the others. But in any case, it is physically impossible to have a spectral line which is characterized by the only natural shape, which leads to the dispersion profile (lorentzian) with the width related to the damping constant of the transition undergone by the emitting source. Physically, the natural line broadening effect is negligible with respect to the other broadening mechanisms discussed above.

The thermal Doppler effect and the Stark effect have attained practical importance for plasma diagnostics since the line width related to each of them is a known function of one or more plasma parameters. For thermal Doppler broadening, the line width and the emitting source kinetic temperature are related through the following equation:

\[ \Delta \nu = \frac{\nu}{c} \left( \frac{kT}{m} \right)^{1/2} \]

where \( \Delta \nu \) is the Doppler width, \( \nu \) is the frequency of the spectral line, \( c \) is the speed of light, \( k \) is the Boltzmann constant, \( T \) is the kinetic temperature of the emitting source, and \( m \) is the mass of the emitting species.
\[ \text{FWHM}_0 = \left( \frac{8kT \ln 2}{(M c)^2} \right)^{1/2} \nu_o \]  

which, after substitution of the respective values for \( k \) and \( c \) and multiplication, becomes:

\[ \text{FWHM}_0 = 7.16 \times 10^{-7} \left( \frac{T}{M} \right)^{1/2} \nu_o \]  

while for the Stark broadening due to electrons, the line width and the electron density are related through the following equation:

\[ \text{FWHM}_e = 2.50 \times 10^{-9} \alpha_{1/2} N_e^{2/3} \]  

In general, the Stark effect is a sensitive broadening mechanism for low atomic/molecular weight radiating species like hydrogen while it is negligible for heavy species like nitrogen. In fact, for hydrogen in an arcjet plume, both Doppler and Stark broadening mechanisms are important over the expected range of kinetic temperatures and electron densities. Theoretically, it can be demonstrated that an arcjet plume with a kinetic temperature for electronically excited hydrogen of about 1,000 K and an electron density of \( 10^{14} \text{ cm}^{-3} \) (which corresponds to a ionization fraction of about 1%), it is reasonable to assume that the FWHM = 0.466 cm^{-1} and the FWHM is about 1.3 cm^{-1} for the Balmer-B line and that the electron temperature range is 5,000 - 40,000 K. This means that while line widths exhibited by heavy radiating species like nitrogen allow for a straightforward temperature measurement through Eq. (1), line widths exhibited by hydrogen allow for electron density evaluations only by taking into account for the Doppler contribution and using the tabulated data available from literature.

Doppler Shift

When a radiating species moves with a velocity which has a \( V_{\text{obs}} \) component along the line-of-sight of the observer, a Doppler shift of the central frequency of the emitted spectral line is observed. Doppler shift and velocity component along the observation direction are related through the following equation:

\[ \Delta \nu = \nu_o V_{\text{obs}} / c \]  

Since the absolute angle between the velocity vector and the thruster axis is unknown, it is necessary to measure two components of the velocity vector in order to evaluate the axial velocity of the volume probed in the plume when assuming cylindrical symmetry.

Results and Discussion

The first step in the analysis of the plume generated by the MOD-B engine while operating with a nitrogen-hydrogen mixture to simulate
hydrazine, was a wide frequency scan from 15,220 cm\(^{-1}\) to 20,610 cm\(^{-1}\). This scan had the aim to determine the species existing in the plume and to identify the Balmer-\(\alpha\) (at 15,233 cm\(^{-1}\)) and the Balmer-\(\beta\) (at 20,564.77 cm\(^{-1}\)) lines. It should be noted that the frequency indicated for the Balmer-\(\alpha\) line is approximated due to the fact that this spectral line is complex. In particular two lines at 15,233.08 cm\(^{-1}\) and at 15,233.36 cm\(^{-1}\) are resolved using the BPD’s emission spectroscopy system when the light emitted by the hydrogen spectral lamp is analyzed. On the contrary, when the Balmer-\(\alpha\) line emitted by the arcjet plume is analyzed the line loses its multiline structure due to the line broadening of its components. Figure 3 shows the frequency spectrum obtained through the wide frequency scan. Other than the expected Balmer lines, the band spectrum of molecular nitrogen and the single spectral lines emitted by atomic nitrogen\(^{(\text{Ref. 23, 27})}\) are recognizable. The intensity of the Balmer-\(\beta\) line is much higher than the intensity of the Balmer-\(\alpha\) line. This is in agreement with what is expected when the energy level diagram of hydrogen is considered. Precisely, the Balmer-\(\beta\) line is due to the transition from the energy level characterized by \(n = 4\) to the energy level characterized by \(n = 2\). The energy level associated with \(n = 2\) can be also reached through two sequential transitions. The first transition, from \(n = 2\) to \(n = 3\) quantum states, is associated with the emission of the Paschen-\(\alpha\) line (53,315 cm\(^{-1}\)) in the ultra-violet region and the second transition, from \(n = 3\) to \(n = 2\) quantum states, is associated with the emission of the Balmer-\(\alpha\) line. Therefore, the \(n = 3\) energy level is an excited quantum state which also receives from the \(n = 4\) energy level. Another peculiarity which is evident through the analysis of Fig. 3 comes from the comparison between the spectral lines shown in Fig. 3 and emitted by nitrogen and hydrogen. As will be discussed in more detail later in this paper, the spectral lines emitted by molecular and atomic nitrogen are much narrower than the spectral lines emitted by hydrogen.

Among the spectral lines shown in Fig. 3, the line at 20,279.47 cm\(^{-1}\) for nitrogen and the Balmer-\(\beta\) from hydrogen have been used for the analysis of the line profiles and the velocity measurements which are presented in this paper.

**Line Profiles and Line Broadening**

The typical line profile exhibited by nitrogen during the analysis of the MOD-B plume is shown in Fig. 4. This spectral line was collected on the thruster axis, 5 mm downstream from the nozzle exit and with a line-of-sight perpendicular to the thruster axis (90° viewing angle). The figure also shows the gaussian fit which agrees with the experimental profile as is theoretically expected for heavy species. The Doppler width is 0.251 cm\(^{-1}\) which corresponds to a kinetic temperature of 8,371 K for \(N_2\). This value shows that, as already observed in previous analysis\(^{(\text{Ref. 21})}\), the Doppler broadening observed in the arcjet plume is not only a thermal Doppler broadening, but also apparently includes a contribution from turbulence and/or unresolved macroscopic motion of the radiating species.

The spectral lines emitted by hydrogen are considerably wider than the spectral lines emitted by nitrogen. For a comparison, the hydrogen Balmer-\(\beta\) line shown in Fig. 5 was collected at the same spacial location as the nitrogen line shown in Fig. 4 and has a line width of 1.95 cm\(^{-1}\). The wider width exhibited by the hydrogen spectral lines compared to nitrogen spectral lines, is due to the larger Doppler broadening suffered by light species and to the Stark effect which is negligible in the case of nitrogen. As has been pointed out for nitrogen, Doppler broadening is apparently due to thermal broadening as well as to turbulence and/or unresolved macroscopic motion of the radiating species. The folding of the gaussian shapes from the two Doppler effects and the lorentzian shape from the Stark effect, generate a typical Voigt profile for the hydrogen spectral lines. The relative contribution of the Doppler and the Stark broadening mechanisms can be evaluated by considering the agreement of the a pure gaussian fit and a pure lorentzian fit with the experimental data. Figures 5, 6 and 7 refer to three analysis performed with a line-of-sight perpendicular to the thruster axis (90° viewing angle), along the thruster centerline at 2 mm, 5 mm and 8 mm from the nozzle exit, respectively. These figures show the ratio between the chi-square for the lorentzian fit and the chi-square for gaussian fit. This statistical ratio shows that the gaussian contribution to the Voigt profile increases when the distance from the nozzle exit
increases and, in particular, 8 mm downstream of the nozzle exit, the lorentzian contribution is negligible. Figure 8 shows an analysis performed 5 mm from the nozzle exit, with a line-of-sight perpendicular to the thruster axis (90° viewing angle) but 8 mm below it. A comparison of Figs. 6 and 8 shows that the Doppler contribution also increases by moving towards the plume edges and, in particular, 8 mm far from the thruster axis, the lorentzian contribution is negligible.

The hydrogen Balmer-β line, Voigt profile line widths are shown in Fig. 9 as a function of distance from the nozzle exit and distance below the thruster centerline. Near the nozzle exit, the line widths are fairly constant except at the extreme plume edge where it becomes smaller while further downstream from the nozzle exit, the line width decreases steadily as a function of distance from the centerline. In addition, a more significant decrease in the line width is apparent as a function of distance from the nozzle exit. Since Doppler broadening due to turbulence and/or unresolved macroscopic motion of the radiating species is apparently the most important cause of the Doppler broadening and causes an increase in the line widths, it is suggested that the increasing gaussian contribution observed at the plume edges and at larger distances from the nozzle exit (corresponding to smaller line widths), is due to a decreasing Stark effect. This could result from the recombination of electrons which causes a decrease of the electron density in these regions. Comparing the width of the Voigt profile obtained in a region where the Doppler and Stark contributions are competitive (for instance on the thruster axis 2 mm from the nozzle exit) with the line width obtained in a region where the Stark effect is apparently negligible (for instance at the plume edges), enables lorentzian broadening to be inferred from tabulated data. These data provided a FWHM of about 1.62 cm⁻¹ which corresponds to an electron density of about $10^{14}$ cm⁻³, 2 mm downstream of the nozzle exit.

The integrated line intensities, as a function of the distance from the thruster axis for three different plume sections perpendicular to the thruster axis, are shown in Fig. 10. Each data point was obtained as the integral of the hydrogen Balmer-β shape with the background subtracted. Due to the broad wings exhibited by this spectral line, which are a peculiarity of Stark broadened spectral lines, the time needed to collect a line profile for each plume station was about 5 minutes. In order to speed up the analysis, only the region below the thruster axis was analyzed. This restriction did not allow for investigation of plume symmetry, but is adequate to investigate the existence of a collisional regime in the plume. For this purpose, the total intensity emitted by a half of each plume section has been inferred. This quantity is indicated with Z in Fig. 10.

The natural decay of the intensity emitted by an atomic transition follows an exponential law with a decay time, $\tau$, which is a characteristic of the atomic transition. The intensity of the observed atomic transition is expected to be reduced by a factor of 1/e after a time of flight of the species equal to the decay time. The distance from the nozzle exit where the excited species can travel in one decay time, $t = \tau$, can be estimated by considering, in the first approximation, the average exhaust velocity inferred through the thruster performance in Table 1. Since the decay time for the Balmer-β is 119 ns and the inferred average exhaust velocity is 3,000 m/s, the intensity would be expected to drop a factor of 1/e at a distance of approximately 0.3 mm from the nozzle exit. The fact that the observed intensity along the horizontal axis is much higher indicates that the upper level of the observed atomic transition is repopulated during the time of flight of the species due to collisions with other atoms or ions in the plume.

Velocity Distributions

The axial velocity component has been evaluated for the hydrogen and nitrogen species. In order to evaluate the average centerline axial velocity of the exhaust plume, the frequency shifts at viewing angles of 108° and 50° were calculated with respect to the peak frequency at 90° (considered as the unshifted frequency). Typical line profiles measured at these three viewing angles for the hydrogen Balmer-β line are shown in Fig. 11. Using the frequency shift observed between these lines, the velocity components at 108° and at 50° were evaluated. The axial velocity component was then calculated through three simultaneous equations (see nomenclature for definition of the indicated quantities):
The centerline axial velocity component \( v_z \) downstream from the nozzle exit has been measured as described above for atomic hydrogen, atomic nitrogen, and molecular nitrogen in order to compare the contribution to the specific impulse coming from these species. On the other hand, since the thruster specific impulse is related to the species velocities inside the nozzle and the velocity measurements are performed outside the nozzle, it is important to study how the velocity drops along the thruster axis. For this purpose, the hydrogen centerline axial velocity component has been measured at three distances downstream from the nozzle exit: 5 mm, 10 mm, and 15 mm. The results are shown in Fig. 12. The centerline axial velocity component for atomic hydrogen and atomic nitrogen seem to be the same within the experimental errors at a station 5 mm downstream from the nozzle exit. The centerline axial velocity component for molecular nitrogen is a little lower. A higher velocity for hydrogen is expected with respect to nitrogen as a consequence of the differences in atomic weights. The centerline axial velocities measured 5 mm from the nozzle exit imply a specific impulse of 255 s for atomic hydrogen and nitrogen and a specific impulse of 228 s for molecular nitrogen. The values for the nitrogen species are consistent with the average specific impulse of 292 s obtained through thrust and propellant mass flow measurement while a value of 255 s for hydrogen is too low. Similar velocities observed for hydrogen and nitrogen can be explained by considering that the collisional regime, discussed earlier to explain repopulation of upper level of hydrogen Balmer-\( \beta \) transition, causes a redistribution of the velocity outside the nozzle.

Figure 12 also shows that the centerline axial velocity component drops rapidly along the thruster axis. The rapid decrease of the velocity along the thruster centerline implies that the collisional regime extends some nozzle radii downstream the nozzle exit and is likely related to vacuum chamber background pressure effects.

Conclusions

The plume of a 1 kWe arcjet operating on a hydrogen-nitrogen mixture to simulate hydrazine was analyzed using emission spectroscopy. This analysis showed that the plume is collision dominated for the atomic transition observed. Integrated line profiles observed at the nozzle exit were gaussian for nitrogen species while they exhibited a Voigt profile for the hydrogen species. Hydrogen line profiles became gaussian in shape several nozzle radii downstream from the nozzle and at the plume edges. Large Doppler widths suggested that additional broadening mechanisms competing with thermal broadening exist. The Stark broadening exhibited by hydrogen at the nozzle exit implied an electron density of about \( 10^{14} \) cm\(^{-3} \).

Measurement of the axial velocity component on the engine centerline provided a value of 2,500 m/s for atomic hydrogen and atomic nitrogen and a value of 2,240 m/s for molecular nitrogen, with the thruster operating at 292 s average specific impulse (as derived from thrust balance and mass flow rate measurements). In the future, the profiles will be examined while operating the arcjet on catalytically decomposed hydrazine and with different internal configurations. The radial velocity distribution will be also investigated and the plume properties closer to the nozzle exit will be examined.

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References


**Figure 1 - Schematic of MOD-B Arcjet.**

**TABLE 1**

Summary of Thruster Operating Conditions for Presented Results

<table>
<thead>
<tr>
<th>Mass Flow&lt;sup&gt;(*)&lt;/sup&gt; (mg/s)</th>
<th>Power (W)</th>
<th>Specific Power (kJ/mg)</th>
<th>Thrust (mN)</th>
<th>Specific Impulse (s)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51 ± 2</td>
<td>910 ± 160</td>
<td>17.7</td>
<td>144 ± 12</td>
<td>292 ± 20</td>
<td>22.9 ± 0.5</td>
</tr>
</tbody>
</table>

<sup>(*)</sup> Propellant: nitrogen-hydrogen mixture simulating hydrazine.
Figure 2 - Schematic of the Emission Spectroscopy System.

Figure 3 - Spectrum observed in emission of MOD-B plume.
Figure 4 - Line profile from nitrogen observed at the thruster centerline and 5 mm from the nozzle exit.

Figure 5 - Line profile from hydrogen observed at the thruster centerline and 2 mm from the nozzle exit. The indicated ratio is the chi-square of the lorentzian fit divided by the chi-square of the gaussian fit.
Figure 6 - Line profile from hydrogen observed at the thruster centerline and 5 mm from the nozzle exit. The indicated ratio is the chi-square of the lorentzian fit divided by the chi-square of the gaussian fit.

Figure 7 - Line profile from hydrogen observed at the thruster centerline and 8 mm from the nozzle exit. The indicated ratio is the chi-square of the lorentzian fit divided by the chi-square of the gaussian fit.
Figure 8 - Line profile from hydrogen observed at 8 mm below the thruster axis and 5 mm from the nozzle exit. The indicated ratio is the chi-square of the lorentzian fit divided by the chi-square of the gaussian fit.

Figure 9 - Line widths of the Voigt profiles from hydrogen as a function of the distance from the nozzle axis for different plume sections.
Figure 10 - Line integrated intensities of the Voigt profiles from hydrogen as a function of the distance from the nozzle axis for different plume sections. $Z$ represents the total intensity collected on each of the analyzed plume sections.

Figure 11 - Doppler shifts observed for hydrogen at three observation angles.
Figure 12 - Centerline axial velocity component for different species existing in the plume of MOD-B.