Overview of Emission Spectroscopic Measurement of an Ammonia Arcjet Plasma Plume

D. Bock[⋆], *G. Herdrich*[⋆], *S. Lein*[⋆], *H.-P. Röser*[⋆] *and M. Auweter-Kurtz*[⋆⋆]
[⋆]*Institut für Raumfahrtsysteme, Universität Stuttgart*
Pfaffenwaldring 31, 70569 Stuttgart, Germany
[⋆⋆]*Universität Hamburg*

Abstract

The Institut für Raumfahrtsysteme, Universität Stuttgart, plans a small satellite mission to the moon – Bw1. The propulsion systems – a cluster of instationary pulsed magnetoplasmadynamic thrusters (SIMP-LEX) and a thermal arcjet thruster (TALOS) with ammonia as propellant – are currently under development at IRS. For better understanding of chemical and physical processes inside the thermal arcjet thruster, the plasma plume is investigated by emisison spectroscopy. Expected results of these measurements are the identification of the species inside the plasma plume as an assumption to develop a chemical model for ammonia simulationg the dissociation and ionization processes taking place during operation of a 1-kW class thermal arcjet thruster. With the hydrogen presence in the plasma, the electron density is calculated out of STARK-broadening of the H_α-line. First pre-tests with an Ocean Optics S2000 mini-spectrometer. The mass flow rate was set to 20 mg/s and 25 mg/s, respectively, for electrical input power between 700 W and 1000 W. The measured spectra allow only a very rough estimation of electron density, because the continuum radiation of the nozzle perturbes the detection of the H_α-line. Nevertheless, the elecetron density is estimated to be in the range of $10^{18}\,\mathrm{cm}^{-3}$. For all measured spectra a very intense signal at 336 nm was detected. As the molecular band head of NH is at 336 nm ($NH\,(0,0)$) and the head of N_2 is at 337.13 nm ($N_2\,(0,0)$) and keeping the resolution of the spectrometer (2.5 nm) in mind the presence of both molecules in the plasma plume is possible. Further emission spectroscopic measurements will have a focus on investigation of the vibrational bands of NH and N_2.

1. Introduction

The Institut für Raumfahrtsysteme (IRS), Universität Stuttgart, has launched a small satellite program in 2002. The last of four academic small satellites – Bw1– is an all electrical mission to the moon.[1] This satellite will use two different thruster systems – a cluster of instationionary pulsed magnetoplasmadynamic thrusters (SIMP-LEX)[2] and a thermal arcjet thruster (TALOS).[3] Both thruster systems are developed at IRS. Thermal arcjet thruster systems are state of the art for use as north-south station keeping devices with hydrazine as propellant on geostationary satellites. The use of a thermal arcjet thruster as one of the main engines for an interplanetary and university led mission is a new approach.

For a better understanding of the thruster performance and plasma physics the knowledge of the plasma composition and characteristics is necessary. This could be conducted by use of different intrusive or non–intrusive diagnostic techniques like Langmuir probes, emission spectroscopy or Fabry-Perot interferometry. As emission spectroscopy is a non-intrusive technique with the possibility to find qualitative and quantitative information about the plasma conditions like electron density, electron temperature and species, it is used here to get a first inside to the ammonia plasma. The combination of the theory of different existing line-broadening mechanisms with the conducted measurements makes the emission spectroscopy an attractive noninterfering diagnostic technique.

Emission spectroscopic measurements for different operation points concerning the mass flow rate and the electrical power are conducted. An estimation of the plasma composition, i.e. the species inside the plasma, and the electron density has been done and a comparison of the results with literature data has been conducted.

This paper focuses on the results received during emission spectroscopic pre-tests conducted during operation of the thermal arcjet thruster TALOS at different operation points using an Ocean Optics S2000 mini-spectrometer. Furthermore, the theoretical approach for an estimation of the expected electron density by use of the detected spectrum is presented. Using these results further emission spectroscopic measurements are goint to be designed.

2. Experimental Apparatus

Spectroscopic measurements are conducted during operation of the thermal arcjet thruster Talos inside a tank under vacuum conditions. The ambient pressure prior to experiment is 4×10^{-3} hPa and during experiment 5×10^{-2} hPa. During the experiments the mass flow of the propellant has been varied as well as the electrical input power. A summary of the different examined operation points is given in table 2. By observation of the outer nozzle temperature of the thermal arcjet thruster by use of a pyrometer the stationary operation points of the thermal arcjet thruster are identified. Optical access during the experiments is possible through windows in the tank walls, the window used for optical access of the spectroemter is made of quarz glass.

Table 1: Test matrix

	Case 1	**Case 2**
Mass Flow (mg/s)	20	25
Electrical Input Power (kW)	0.7, 0.8, 0.9, 1	0.7, 0.8, 0.9, 1

The propellant is fed from an ammonia bottle through pipings made of stainless steel. The measurement and adjustment of the mass flow is carried out by a thermal mass flow controller. The mass flow controller has been calibrated by direct weight measurement with a so-called "sartorius-balance" prior to the experiments. Thrust is measured by use of non-contact displacement sensor measuring the deflection of the pendulum type thrust stand, to which the thruster is mounted. The thrust measurement system is calibrated prior to every experiment.

The current supply of the thermal arcjet thruster is accomplished by a laboratory power control unit (Pcu). It provides a decent current of up to 25 A, which can be adjusted stepless, at voltages between 50 V and 140 V. The switch voltage is about 2000 V. Control and data acquisition is accomplished by a Pc.

The spectrometer used is an Ocean Optics S2000 type grid mini-spectrometer. The integration time can be adjusted and is set to 10 ms for all conducted measurements. The spectrometer has a 600 line grid and a resolution of about 2.5 nm. The integrated CCD-Chip contains 2048 Pixel. Figure 1 (*left*) shows a setch of the overall test setup and fig. 1 (*right*) a schematic of the optical configuration.

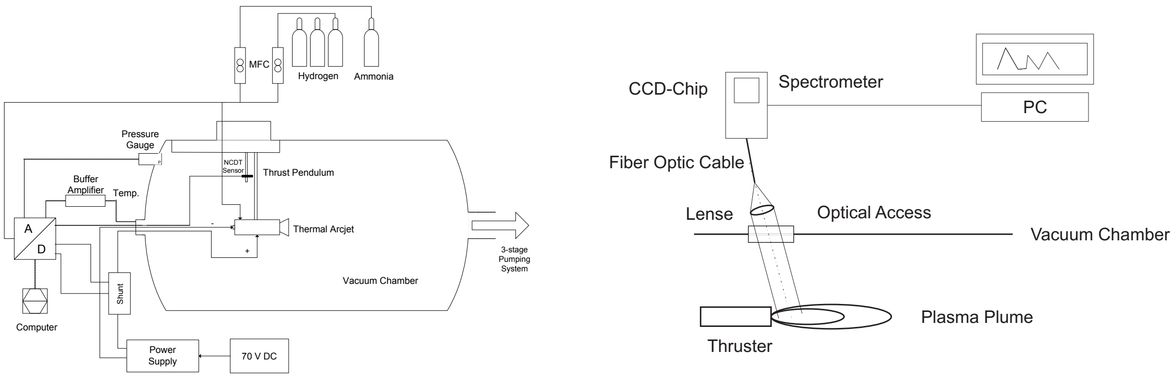

Figure 1: Test facility (*left*) and schematic of optical configuration (*right*)

2.1 Thermal Arcjet Thruster

The emission spectroscopic measurements are conducted with the laboratory model of the thermal arcjet thruster. The overall design of the thermal arcjet thruster is shown in fig. 2. The propellant – gaseous ammonia – is heated by an arc, which builds up between cathode and anode. Due to the heating the ammonia is dissoziated and partially ionized. Acceleration takes place by the heating process and expansion through the Laval-nozzle. The power level of the thermal arcjet thruster is in the 1 kW-class.

Figure 2 (*left*) shows a sectional drawing of the thruster laboratory model and the thruster during operation with ammonia fig. 2 (*right*), respectively. During the development process of the thermal arcjet thruster the cathode gap can be adjusted stepless and the nozzle geometry can be changed by keeping the outer nozzle geometry constant and changing the inner geometry like the nozzle throat diameter, the nozzle throat length amd the expansion angle.

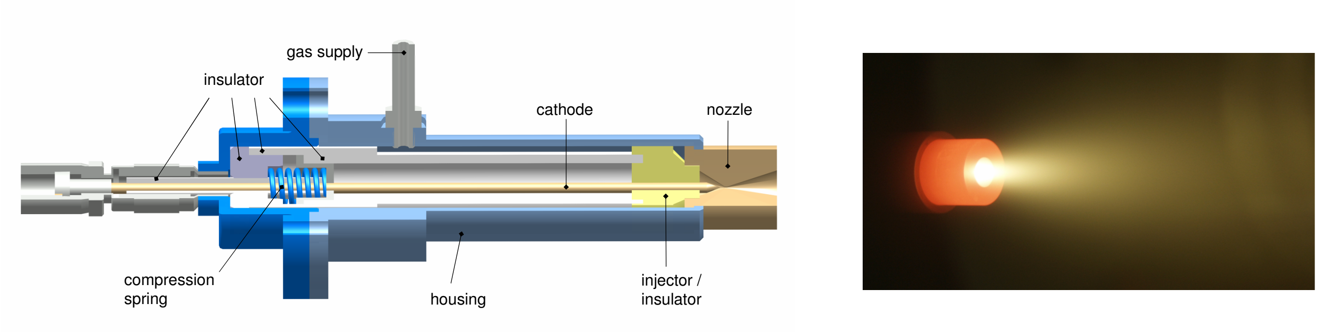

Figure 2: Sectional drawing of thruster (*left*) and thruster during operation (*right*)

The cathode is made of 2% thoriated tungsten and is 3 mm in diameter. The cathode tip is a cone with 22.5° half cone angle. The radiation-cooled nozzle has a converging half cone angle of 35° and the half cone angle of the diverging part is 19°. The nozzle throat diameter is 0.6 mm, the nozzle throat lenth 0.7 mm and the area expansion ratio is $\varepsilon = 257$. The nozzle is made of a tungsten alloy containing 1% lanthanum oxide. The typical temperature of the outer nozzle surface during stable operation is about 1100°C.

3. Theoretical Estimate of Plasma Parameters

As the dissociation and ionisation of the propellant is one of the basic loss mechanisms in thermal arcjet thruster the knowledge of the degree of ionization has the potential for thruster optimization. For this purpose the electron density as well as the particle density inside the plasma is needed.

The particle density of the plasma at the exit nozzle plane can be estimated by use of the continuity equation (1)

$$\dot{m} = \rho \, c_e \, A_e \tag{1}$$

with $\dot{m}$ as the mass flow rate, ρ as the density, c_e as the effective exhaust velocity and A_e the exit plane area of the nozzle. Under consideration of the ideal gas law according to equation (2)

$$p = n \, k \, T = \rho \, R \, T \tag{2}$$

with p as the pressure, n as the particle density, k the Boltzmann constant, R the specific gas constant and T the Temperature, an estimation of the particle density at the nozzle exit plane can be conducted according to equation (3).[4]

$$n = \frac{\dot{m} \, N_A}{\bar{M} \, A_e \, c_e} \tag{3}$$

Here, N_A is the Avogadro constant, $\bar{M}$ the mean weight of the propellant.

Prior to calculation of the electron density number inside the plasma plume, the dominant broadening effect has to be identified. In general, the dominant line-broadening mechanisms in plasmas are the Doppler effect and the Stark effect. The Doppler effect is caused by the movement of the radiating particles toward or away from the observer leading to a shift in wavelength. The Stark effect is caused by the interactions between charged particles. According to Huddlestone[?] Doppler-broadening is the dominant line-broadening mechanism in plasmas of low electron density and high temperature, whereas Stark-broadening prevails for the reversed conditions. It is assumed that for the investigated plasma the temperature is low ($T < 10^4 K$) and the electron density is high ($n_e > 10^{16}$ cm^{-3}).[4] Thus, the line-broadening mechanisms is Stark-effect dominated and for the calculation of the electron density inside the plasma by use of the spectrum gathered during experiment equation (4) is used,

$$\Delta\lambda_{1/2} = 2.5 \, 10^{-9} \, \alpha_{1/2} \, n_e^{2/3} \tag{4}$$

with $\Delta\lambda_{1/2}$ ($\Delta\lambda/2$) as the half width in Å, $\alpha_{1/2}$ as the theoretical half width, which corresponds to the value of α where the reduced STARK profile $S(\alpha)$ is one-half of its maximum value, and N as the ion density. Assuming a quasi-neutral plasma the ion density N is equal to the electron density n_e.[5]

According to Griem[7] α is defined by equation (5).

$$\alpha = \frac{\Delta\lambda}{F_0} \tag{5}$$

Here, F_0 is the normal field strength according to equation (6).

$$F_0 = 1.25\,x\,10^{-9} N^{2/3} \tag{6}$$

Other than all equations used in this paper the previous three equations (eq. (4), eq. (5) and eq. (6)) are in the cgs-Gaussian unit system instead of the mks-system.

4. Results and Discussion

For the investigated plasma, the mass flow rate $\dot{m}$ is set to 20 and 25 mg/s, respectively. The exit plane area is specified by the thruster geometry and as the geometry is constant for all conducted tests. The effective exhaust velocity c_e varies by variation of the mass flow rate and the electrical input power of the thruster. The effective exhaust velocity is calculated out of the thrust ($F = \dot{m}\, c_e$), which is measured continuous during experiment.

For caclulation of the particle densities according to eq. (3) the mean molecular weight depends on the degree of dissociation in the plasma. It is assumed that the plasma at the exit of the nozzle is nearly completely dissociated. The mean molecular weight for completely dissociated ammonia is 4.25 g/mol.[6] This leads to particle densities about $n = 3\,x\,10^{21}$ m^{-3}.

Figure 3 shows two spectra measured during experiment – one ammonia and one hydrogen spectrum. The mass flow of the ammonia is 20 mg/s and the electrical input power is 1000 W. For comparison the measured spectrum for the same thruster operated with hydrogen (mass flow 11 mg/s and electrical power 900 W) is shown. One can clearly identify the first four Balmer lines (H_α to H_δ) during operation with hydrogen. The spectrum of operation with ammonia shows an additional signal of high intensity at about 336 nm and the H_α line can be identified but has less intensity. Additionally, continuum radiation of the nozzle perturbs the detection of the H_α line. The H_β line cannot be identified clearly.

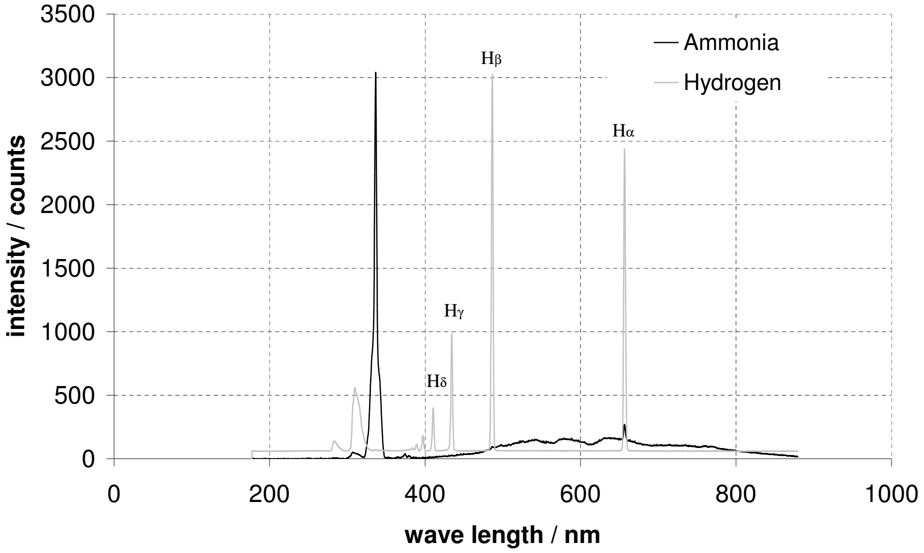

Figure 3: Measured spectrum / mass flow 20 mg/s and electric power 1000 W

This phenomenon of perturbation due to the continuous radiation of the nozzle was present for all measurements conducted with ammonia as propellant. Therefore, only a very rough estimation of the electron density could be done using this spectra. The perturbation arises druing ammonia operation, because the measurement point has to be moved closer to the nozzle exit plane to detect the signal of the hydrogen radiation.

With this information the electron density inside the plasma is calculated according to equation 4 to be between $n_e = 8 \text{ x } 10^{17}\ \text{cm}^{-3}$ and $n_e = 2.5 \text{ x } 10^{18}\ \text{cm}^{-3}$ with the parameter $\alpha_{1/2}$ being between 0.005 and 0.01 according to Griem.[7] The uncertainty of the calculation in in the regime of 45%, caused by the uncertainty of the $\Delta\lambda_{1/2}$ determination, the $\alpha_{1/2}$ determination and the uncertainty of the calculation method itself according to Griem.[?]

Table 2: Comparison of electron density with literature data

	Carney[8]	**Zube**[4]	**This work**
Electron Density (m^{-3})	$5\,x\,10^{15}$	$1\,x\,10^{20}$	$8\,x\,10^{23} - 2.5\,x\,10^{24}$
Electrical Power (W)	1000	750	1000
Mass Flow (mg/s)	52	22.5	20
Diagnostic Tecnique	Langmuir Probe	Emission spectroscopy	

[a] Propellant for all thruster is ammonia

Carney[8] did the measurements in the far field plume – 32 cm away from nozzle exit plane, whereas Zube[4] and in this work the measurements were conducted in the near field of the plasma plume (up to 30 mm behind the nozzle exit plane). This is one reason why the electron density is measured by Carney is much lower than measured by Zube and in this work. Furthermore, the increased mass flow during the measurements of Carney is an explanaition for the lower electron density inside the plasma compared to this work, because for the same input power less ionization occurs at higher mass flow rates. The nozzle geometry was similar for all three investigated thrusters.

For comparison of the results by Zube[4] and this work one has to keep in mind that for the electron density presented here the line of sight is increased due the fact that the measurements were taken not perpendicular to the plasma axis. Furthermore, neither the line broadening induced by the DOPPLER effect nor the line broadening induced by instrumental limitations – the apparent broadening – is considered for the calculation of the electron density. Recapitulatory, one would expect estimation of the highest expected electron density inside the plasma by using the method described in this paper.

The signal with high intensity at 336 nm was present for all measurements, i.e. all set mass flow rates and power levels. As the resolution of the spectrometer is 2.5 nm this could either be NH as the maximum of the corresponding molecular NH band is at 336 nm (NH (0,0)) or N_2 with a band maximum at 337.13 nm (N_2 (0,0)). According to literature data, it is assumed that the fraction of NH inside the plasma is much greater than the fraction of N_2 and thus the 336 nm signal corresponds to the molecular band of NH.[4,9]

5. Conclusions and Future Work

This paper presents the results of electron density estimation out of emission spectroscopic measurements conducted during thermal arcjet thruster operation at a mass flow rate of 20 mg/s and 25 mg/s, respectively, and an electrical input power between 700 W and 1000 W. An Ocean Optics S2000 mini-spectrometer with a resolution of 2.5 nm has been used for measurement of the plasma spectrum. The measured spectra all give a signal at 336 nm with a relatively high intensity. The H_α-line is partly screened by the continuum radiation of the thermal arcjet thruster nozzle, so that only one spectrum (20 mg/s, 1000 W) could be used for calculations. The electron density is found to be about $2.5\,x\,10^{24}\text{m}^{-3}$ with an uncertainty of about 45 %. Seeing that the test conditions were suboptimal (line of sight not perpendicular to the plasma plume axis) and the used theory for calculation only considered STARK-broadening effects, the electron density has to be considered as the maximum electron density. According to the observations of Zube[4] it is assumed that NH is present in the plasma and the signal at 336 nm is the vibrational band $NH(0,0)$.

The experimental setup will be enhanced to get optical access perpendicular to plasma plume axis. By use of a two-axis linear step motor it will be possible to move the focus point of the spectrometer along the plasma plume axis as well as perpendicular to this axis. Doing so, one can calculate radial profiles of the electron density at different axial positions. By comparison of the intensities of the H_α and H_β-line – if both are signals are detected – the hydrogen excitation temperature will be calculated according to Zube.[4]

6. Acknowledgments

The authors wish to thank the ’Landesgraduiertenförderung Baden-Württemberg’ for their financial support.

References

[1] Laufer, R. An all Electrical Small Satellite for a Telchnology Demonstration and Science Mission to the Moon. In *55th International Astronautical Congress of the International Astronautical Federation*, Oct. 4-8, 2004.

[2] Nawaz, A., Auweter-Kurtz, M., Herdrich, G. and Kurtz, H. L.. Impulse Measurements and Thermal Investigation of SIMP-LEX. In *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, July 9-12, 2006.

[3] Bock, D., Auweter-Kurtz, M., Kurtz, H. L. and Röser, H.-P.. Experimental Investigation on Thermal Arcjet Thruster Development for a Science Mission to the Moon. In *57th International Astronautical Congress*, October 2-6, 2006.

[4] Zube, Dieter M. and Messerschmid, Ernst W. Spectroscopic Temperature and Density Measurements in Low Power Arcjet Plume. In *30th Joint Propulsion Conference*, June 27 - 29, 1994.

[5] Huddlestone, R. H. Plasma Diagnostic Techniques. *Academic Press* 1995.

[6] Auweter-Kurtz, M. Lichtbogentriebwerke für Weltraumaufgaben. *B.G. Teibner*, 1992.

[7] Griem, Hans G. Plasma Spectroscopy. *McGraw-Hill Book Company*, 1994.

[8] Carney, L. M. and Sankovic, J. M.. The Effects of Arcjet Operating Condition and Constrictor Geometry on the Plasma Plume. In *25th Joint Propulsion Conference*, July 10-12, 1989.

[9] Tahara, H., Yonezawa, T., Andoh, Y. and Yoshikawa, T.. Emission Spectroscopic Measurement of Ammonia or Mixture of Nitrogen and Hydrogen in a Direct-Current Arc Jet Generator with an Expansion Nozzle. *IEEE Transactions on Plasma Science*, Vol-26, No.4, August 1998