NEUTRAL GAS TEMPERATURE MEASUREMENTS OF A RADIO FREQUENCY MICRO-THRUSTER

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Abstract

A radio frequency (13.56 MHz) capacitively coupled cylindrical argon plasma discharge was analysed using optical emission spectroscopy (OES) for various powers and pressures in the ranges 5 W to 40 W and 0.5 Torr to 4 Torr. Trace amounts of nitrogen were added to the discharge to estimate the temperature of the neutrals using rovibrational band matching of the 2nd positive system of nitrogen. Comparing simulated computer generated spectra of these bands to experimentally measured spectra determined preliminary results for the rotational and vibrational temperatures of the nitrogen gas, from which the temperature of the neutrals was inferred by assuming the rotational temperature was the same as the neutral gas temperature.

INTRODUCTION

The development of increasingly smaller satellites and spacecraft has in turn developed a need for micro-thrusters that have low mass, volume and power consumption. Electric propulsion is favourable in such circumstances as the specific impulse is much higher than conventional chemical rockets [1]. Hall and gridded ion thrusters are current highly developed electric propulsion systems, however, these systems lose efficiency when scaled down [2]. Alternate options for electric micro-thrusters include resistojets and arcjets [1], hollow cathode thrusters [1,3] and radio frequency (RF) capillary discharge [4].

Another possible micro-thruster electric propulsion system consists of a capacitively coupled RF discharge (13.56MHz) within a tube with a 4.2mm inside diameter and 20mm length known as Pocket Rocket [5]. Gas, usually argon, is introduced to the system via an upstream plenum chamber with pressures around a few Torr. Electrodes placed around the Pocket Rocket tube create a cylindrical plasma discharge which is expanded into a vacuum. The discharge is weakly ionized (less that 1%) due to the higher pressures [6], therefore direct thrust from ion acceleration is negligible. However, the ions would typically reach a Bohm velocity in the order of 3000ms^{-1}, much greater than a typical thermal gas velocity of 300ms^{-1}. Charge exchange collisions between ions and neutrals may therefore result in neutral gas heating within the discharge and the thrust produced by the device will be increased over a cold gas thruster. Increased thrust from neutral gas heating makes Pocket Rocket a potentially viable micro-thruster for micro-satellites.

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Previous experiments performed using a Langmuir Probe to determine the electron temperature of the Pocket Rocket discharge estimate the neutral gas temperature as 3200K at 10W and 1.5 Torr [6]. In the same paper, power coupling calculations relating the input power to discharge velocity estimated the neutral gas temperature for the same conditions much lower at 1430K.

To determine the temperature of the neutrals in the discharge, a non-invasive spectroscopy method was used where a small amount of nitrogen gas added to the discharge produces rovibrational spectral bands. The measured bands can be compared to simulated spectra to determine the rotational and vibrational temperature of the nitrogen molecules, from which the neutral gas temperature is inferred as the rotational temperature. This technique has been previously used to determine the temperature of similar discharges [7,8].

EXPERIMENTAL SETUP

The Pocket Rocket device, as shown in Figure 1(a) consists of a 4.2mm inside diameter, 1.3mm thick, 20mm long alumina tube. Argon gas is introduced to the system through an upstream plenum chamber with a diameter of 40mm and a length of 12mm. A 6mm wide copper electrode surrounds the tube at the midway point with two 3mm wide copper grounded electrodes placed either side at a distance of 3mm, creating a capacitively coupled discharge inside the tube. The discharge expands into a 750mm long, 50mm diameter evacuated glass tube which is itself attached to a vacuum chamber (160mm diameter, 300mm length) equipped with a primary rotary oil pump. A Convectron gauge measures the pressure in the upstream plenum, while a Baratron gauge measures the pressure in the vacuum chamber. The base pressure in Pocket Rocket is in the order of 10^{-3} Torr. Operating pressures measured in the plenum chamber ranged from 0.5 Torr to 4 Torr, resulting in vacuum chamber pressures approximately 2.2 times lower, from 0.2 to 1.8 Torr.

Power from an RF generator (13.56MHz) ranging from 5-40W is coupled to the system through a pi-matching network. The current and voltage supplied to the electrode are measured using a Rogowski coil and a 1/1000 high voltage probe respectively. In addition, a Bird power meter and standing wave ratio (SWR) meter are inserted between the RF generator and the matchbox to measure the forward and reflected power.

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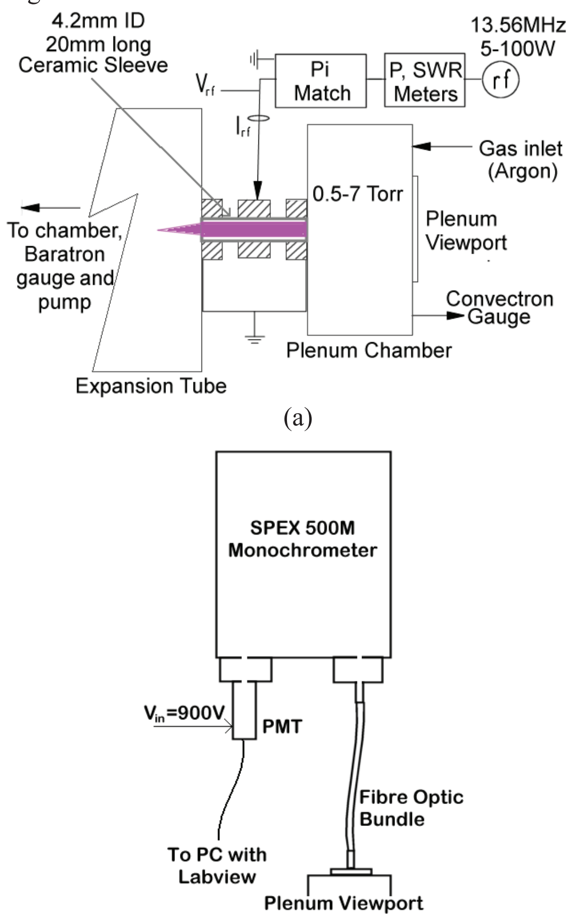
The spectroscopy system, as shown in Figure 1(b), consists of a SPEX 500M monochromator with 500mm focal length, 50mm slit widths and a 1200 groove/mm grating is used in conjunction with a 4mm diameter, bifurcated fused silica fibre-optic bundle to direct light from the discharge onto a Hamamatsu C1053 photomultiplier tube (PMT). A specially designed Labview program is used to scan the monochromator over the wavelength region from 365nm to 392nm (with the data later trimmed to 365nm-381nm), simultaneously recording the data from the PMT. 12000 samples taken at 12000Hz were recorded and averaged using a PMT bias voltage of 900V.



(a)

(b)

Figure 1: Experiment setup (a) Pocket Rocket System and (b) Spectroscopy equipment setup

SIMULATED SPECTRUM

As nitrogen (N_2) is a diatomic molecule it can undergo rotation and vibration as well as translation. The molecule can only exist in discrete energy levels for both rotation and vibration corresponding to the quantum numbers, denoted by J and v respectively. Transitions from an upper energy level (denoted by `) to a lower energy level (denoted by ``) release energy packets in the form of photons with different wavelengths depending on the transition. The intensity of the photons emitted depends on the rotational and vibrational temperature of the molecule. Therefore, using optical emission spectroscopy (OES), the wavelengths of the emitted light and the respective intensities can be used to determine the rotational and vibrational temperature of the molecule, and from that the neutral gas temperature implied.

The second positive system of nitrogen ($C^3\Pi \rightarrow B^3\Pi$) in the wavelength region from 365-381nm was chosen for this experiment. This wavelength region presents minimal interference from strong argon lines and the required constants are readily available as this system has been used in multiple previous works [7,8,9]. The vibrational transitions used were (0,2), (1,3), (2,4) and (3,5). For each vibrational transition, 100 J values were used.

The method of deriving the following equations will not be covered here but Herzberg [10] and Barrow [11] cover the procedure very well.

The vibrational and rotational energy of a diatomic molecule can be inferred from a quantum mechanical analysis of a non-rigid rotor (rotational) and anharmonic oscillator (vibrational) [10,11]. The resulting allowed energies for a nitrogen molecules rotation (E_J) and vibration (E_v) truncated to include only second order terms are

$$E_{J'} = hcB_{v'}J'(J'+1) + hcD_{v}J'(J'+1)^2$$

$$E_{v'} = hc\omega_e(v'+1/2) - hc\omega_e x_e(v'+1/2)^2$$

where h is Planck's constant, c is the speed of light in vacuum, B_v and D_v are rotational constants taken from Herzberg [10, pg 106-107 and 12, pg 418] and ω_e and $\omega_e x_e$ are vibrational constants also taken from Herzberg [12, pg 418]

The wavelength (λ) of each transition is found using the basic relation $\frac{1}{\lambda} = \frac{\Delta E}{hc}$. Taking into account coupling of rotational and vibrational energies [12] the resulting equation becomes

$$\lambda_{Bv''J''}^{Cv'J'} = \Big\{ n_a \sum_{pq} Y_{pq}^{C}(v'+1/2)^p[J'(J'+1)]^q - Y_{pq}^{B}(v''+1/2)^p[J''(J''+1)]^q \Big\}^{-1}$$

where n_a is the refractive index of air. The subscripts p and q refer to the powers of the vibrational and rotational quantum numbers respectively. The constants Y_{pq} are Dunham coefficients and are amalgamations of the various constants resulting from the energy coupling for each of the power terms [13]. These were taken from Bai *et al.* [8] for values of p from 0 to 5 and q from 0 to 2.

The next step is to determine the intensity of the spectrum for each wavelength. It is assumed that the N_2 gas can be described by a Maxwell-Boltzmann distribution about a single rotational and vibrational temperature. Therefore, the intensity of the spectral line at each wavelength is given by

$$I_{Bv''J''}^{Cv'J'} = \frac{D}{\lambda^4} q_{v',v''} e^{\frac{-E_{v'}}{kT_v}} S_{J',J''} e^{\frac{-E_{J'}}{kT_r}}$$

where D is an arbitrary constant depending on the equipment used, $q_{v',v''}$ are the Franck-Condon factors

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taken from Zare [14] and $S_{J',J''}$ the Holn-London factors calculated from Herzberg [10, pg 208].

Finally, to make the simulated spectrum match the observed spectrum a line broadening factor is included, determined by the particular spectroscopy apparatus used. The line broadening term used in this work was taken from Phillips [9] as

$$g(\Delta\lambda) = \frac{a-(2\Delta\lambda/W)^2}{a+(a-2)(2\Delta\lambda/W)^2}$$

where W is the full width half maximum and the wings extend to $\pm\frac{1}{2}Wa^{1/2}$. Values for a and W were determined experimentally by measuring the Hg546nm line.

Monte Carlo Markov Chains were used for fitting the measured and simulated data, resulting in a range of credible values for T_r and T_v. From the distribution of the returned values, a 95% credibility range for the temperature can be stated.

RESULTS

The raw spectral data obtained from the PMT tube was affected by relatively large background noise. A Matlab program was written to remove the noise using a smoothing function and subtract the baseline from the data. In addition, some argon peaks visible in the region of interest, identified by recording the spectrum of an argon only plasma to determine the wavelength and intensities of the relevant lines, were removed from the final nitrogen spectrum. The large amount of post-processing may affect the accuracy of the experimental data and reduce the accuracy of the gas temperature determined. However, the preliminary experimental data obtain is sufficient to demonstrate the validity of matching a simulated spectrum to the experimental data for this discharge and provide preliminary results regarding the neutral gas temperature of the discharge and the related trends with pressure and power.

An example of the experimentally determined spectrum is shown in Figure 2, for a 10 W, 1.5 Torr argon-nitrogen plasma discharge. The simulated spectrum overlaid with the same measured data is shown in Figure 3. The resulting temperatures determined were $1605 \pm 15K$ for rotational and 3905K for vibrational, inferring a neutral gas temperature $T_g = 1605 \pm 15K$. This value is within the order of the temperature estimates from the power coupling and Langmuir probe estimates discussed in the introduction, of 1430K and 3200K respectively [6].

Two independently developed codes were also used to check the measured and simulated spectra, one from the Open University in the United Kingdom and the other from the York Plasma Institute at the University of York. The Open University code compared the measured and simulated data over all four bands, determining temperatures of $T_v = 4050K$ and $T_r = 1570 \pm 75K$. The University of York code compared only the highest intensity band around 380nm to determine a rotational temperature of $T_r = 1530 \pm 25K$.

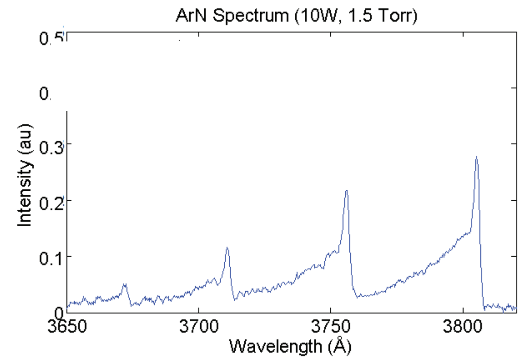

Figure 2: Measured spectrum for a 10W, 1.5 Torr argon nitrogen plasma.

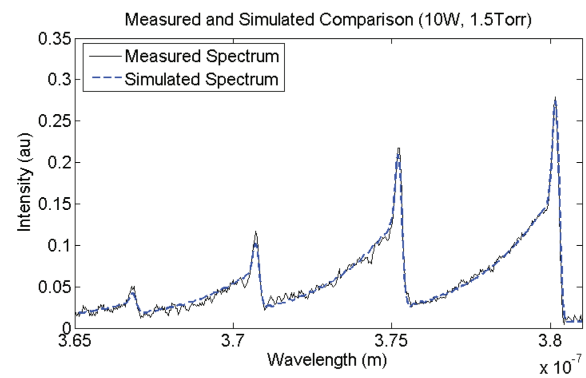

Figure 3: Measured and simulated spectrum for a 10W, 1.5 Torr argon nitrogen plasma.

The range of temperatures determined with this simulated spectrum is completely within the range of temperatures determined using the Open University code. As these codes were developed independently, the overlap demonstrates the simulated spectrum code is producing expected values. The temperature range found by the York Plasma Institute is slightly lower. However, the York code only analysed one band of the spectrum and would therefore be expected to produce slightly different results.

Measured spectra were taken for discharges ranging from 5W to 40W and 0.5 Torr to 4.0 Torr allowing analysis of the gas temperature for various operating conditions. The estimated neutral gas temperatures over the range of operating conditions and corresponding trends for changing power and pressure are shown in Figure 4. These preliminary results show power has an inverse effect on the neutral gas temperature and pressure has a large non-linear effect.

The main method for transferring energy to the neutrals, thereby producing neutral heating, occurs through ion-neutral collisions. The amount of energy transferred, therefore the temperature attained by the neutrals, is directly related to the Bohm velocity of the ions, $v_{B=}\left(\frac{eT_e}{M_i}\right)^{\frac{1}{2}} \approx 2700ms^{-1}$, where T_e is the electron temperature, e is the charge on an electron and M_i is the mass of the ion [15]. The higher the Bohm velocity, the

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more energy is available for transfer and the higher the resulting neutral gas temperature.

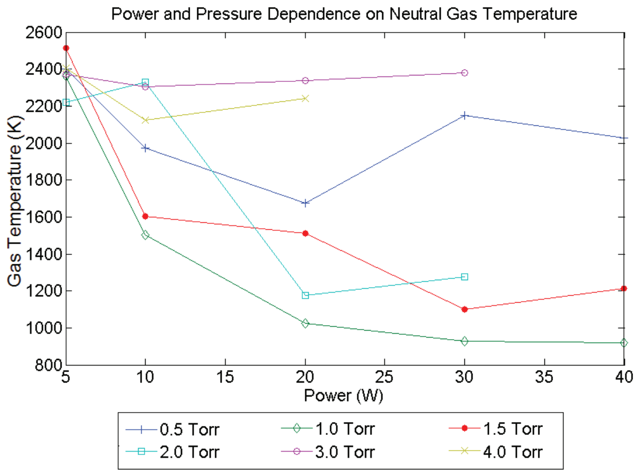

Figure 4: Neutral gas temperatures for an argon nitrogen plasma discharge for input powers of 5-40W and upstream pressures of 0.5-4.0Torr.

The change in neutral gas temperature with power is an inverse relationship with a large decrease at lower powers, tapering off to a more linear relationship as power increases. Changes to the input power of a capacitively coupled plasma have been shown to have little effect on the electron temperature [16,17]. As Bohm velocity is directly proportional to the square root of electron temperature, this would result in relatively constant neutral gas temperatures with increasing powers. However, as power increases the mode of excitation of the nitrogen molecules changes from rotational to vibrational. The rotational modes, which are the modes directly related to the translational temperatures, require lower energies to reach excited states than the vibrational modes. As the power increases, the main excitation mode shifts from rotational to vibrational, resulting in a decrease in rotational temperatures and an increase in vibrational temperatures. This is supported by the measured trends between rotational and vibrational temperatures for various powers, shown for 1.0 Torr as an example in Figure 5.

There are two main parameters affecting the relationship between neutral gas temperature and pressure. Firstly, increasing pressure decreases the electron temperature with an inverse relationship [16]. Therefore, increasing the pressure will decrease the Bohm velocity and the neutral gas temperature. However, the mean free path between charge exchange collisions is $\lambda_{cx} = \frac{1}{n_g \sigma_{cx}}$, where n_g is neutral gas density and σ_{cx} is the charge exchange cross section [15]. An increase in neutral gas density resulting from higher pressures, decreases the mean free path between charge exchange collisions and the number of collisions will increase. A higher number of collisions results in a higher transfer of energy and a higher neutral gas temperature.

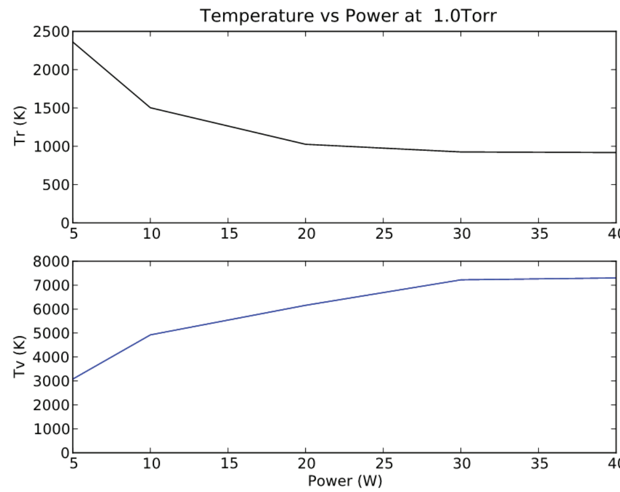

Figure 5: Change in rotational and vibrational temperature with power for a 1.0 Torr argon-nitrogen plasma.

These two aspects combined may explain the non-linear trend between neutral gas pressure and temperature. Further investigations into these results is needed to better understand the findings.

To enable a strong enough nitrogen signal to be detected with the current equipment setup, the argon-nitrogen plasma contained 90% argon and 10% nitrogen. With 10% nitrogen in the mixture the plasma properties are different from a pure argon plasma. For example, mixtures of nitrogen over a few per cent will decrease the plasma temperature [18]. To enable a more accurate estimate of the gas temperature the percentage of nitrogen in the discharge needs to be reduced. Additionally, the relatively large background noise levels in the raw measured data that lead to large amounts of post processing should be reduced. In order to improve both these issues, a charged-couple device (CCD) array will be used to repeat this experiment, allowing for a lower nitrogen per cent in the plasma and lower background noise levels.

CONCLUSION

Preliminary measurements of the neutral gas temperature of a radio-frequency capacitively coupled cylindrical argon plasma discharge, for use in a plasma micro-thruster, were determined using OES. Measurements were made for pressures between 0.5 Torr and 4.0 Torr and powers between 5W and 40W. Neutral gas heating was shown to occur for all pressures and powers tested. It was determined that gas temperature was dependent on both pressure and power. Knowledge of the effect of power and pressure on the gas temperature of the discharge will allow optimisation of the micro-thruster properties.

While the method of matching a simulated spectrum to experimentally determined data has been shown to be viable in this situation, to obtain more accurate results

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using the current method, the experimental data capture method needs to be refined to reduce the background noise level. Reducing the background noise level will allow for more accurate determination of the neutral gas temperature and measurements of error on the experimental data as well as the matched spectrum.

Future works on this theme will investigate different gases used for the discharge, such as pure nitrogen and carbon dioxide, to determine the effect of discharge species on the gas temperature.

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