A simple electric thruster based on ion charge exchange

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An electric thruster is presented that makes use of the properties of an asymmetric hollow cathode glow discharge that ejects a collimated plume of high velocity neutral atoms. Ions are accelerated electrostatically outwards from within the asymmetric hollow cathode and undergo charge exchange with the background gas resulting in energetic neutrals being ejected, thus producing thrust. This thruster is entirely self-contained allowing thrust generation and beam neutralization within the discharge. Doppler spectroscopy was used to determine the speed of atomic hydrogen in the plume and was found to produce a specific impulse greater than 3×10^4 s for applied voltages and powers of the order of 5 kV and 100 W, respectively. An estimate of the thrust of 1 mN for a power input in the order of 1 kW was obtained from previously measured ion densities in similar discharges.

Nomenclature

$\Delta\lambda$ = Doppler shifted wavelength
v = Speed of an excited atomic hydrogen
c = Speed of light
λ_0 = Hydrogen H_α wavelength (656.3 nm)
θ = The angle between the plume direction and the line of sight of the spectrometer
F_T = Thrust
n = Number density of energetic atomic hydrogen
m = Mass of atomic hydrogen
A = Area of the nozzle exit
η = Thruster efficiency

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I. Introduction

We report on a new type of thruster for electric propulsion, with high specific impulse ($\approx 3 \times 10^4$ s), that uses the properties of a hollow cathode discharge to eject energetic neutral atoms. It uses gaseous fuel and does not need accelerating grids or neutralizing electron sources. A high specific impulse thruster will produce greater spacecraft velocity and use a smaller mass and volume of fuel. As a result, less gas would need to be carried by the spacecraft for a given mission compared to an identical unit with a lower specific impulse value.[1] Conversely, higher specific impulse has the effect of reducing the available thrust.[2] High specific impulse thrusters, such as this unit, are suited to low thrust applications like station keeping[3] where small thrust values but high propellant efficiency are required. Field Emission Electric Propulsion (FEEP) thrusters, which have similar thrust and specific impulse values, have been used with success in high precision station keeping[4] and thus this current design would find uses in similar mission scenarios.

The hollow cathode is commonly used in electric propulsion applications as an electron source for ionization, and as a neutralizing source in the plasma plume. However, there have been suggestions of the potential use of a hollow cathode as a stand-alone electric thruster because of the ejection of energetic ions when operated in the high current range.[5–7] Recent work on hollow cathode discharges has shown that energetic neutral atoms can also be ejected from a hollow cathode in the low current regime.[8] This latter work has emerged from ion energy and flow direction measurements carried out on small devices that produce nuclear fusion by inertial electrostatic confinement (IEC) of ions.[10] These devices usually consist of a concentric spherical cathode and anode where the inner and outer spheres are the cathode and anode, respectively. The cathode usually consists of a spherical grid of wires such that it is more than 80% transparent to ions. Collimated plumes emerge from the apertures of the cathode in the tens of millitorr pressure range, otherwise known as a 'star mode' discharge[11] due to the emission of plumes in three dimensions.

Langmuir probe measurements have shown that there is a potential hill within the cathode.[12,13] The height of the potential is slightly less than the applied voltage[13] and is believed to form by the convergence of ions to the cathode centre. Cold ions are also created within the cathode centre due to secondary electron emission from the cathode surface and produce a relatively dense discharge. These cold ions then accelerate down the potential hill, producing diverging ion motion within the cathode, and then undergo charge exchange with the background gas, at pressures in the order of ten millitorr, resulting in a beam of energetic neutral atoms.

There are three principal charge exchange reactions[14] for hydrogen ion beams in the units and tens of millitorr pressure range (used in the thruster) given by the following:

$$\begin{aligned} H^+ + H_2 &\rightarrow H^* + H_2^+ \\ H_2^+ + H_2 &\rightarrow H^* + H + H_2^+ \\ H_3^+ + H_2 &\rightarrow H^* + H_2 + H_2^+ \end{aligned} \tag{1}$$

Ions (H^+, H_2^+, H_3^+) from within the hollow cathode are accelerated by the potential hill outwards. These ions are subsequently involved in charge-exchange reactions with the background gas (H_2). This results in energetic and excited neutrals, H^*, that are able to leave the cathode in the plume, and emit a Doppler shifted spectrum. The Doppler shifted wavelength, $\Delta\lambda$, is given by

$$\Delta\lambda \approx \frac{v \cos\theta \lambda_0}{c} \tag{2}$$

where λ_0 is the wavelength of the unshifted H_α line (656.3 nm), v is the speed of an excited atomic hydrogen, θ is the angle between the observation direction and the axis of the ion channel, and c is the speed of light.

The neutral beams are symmetric about the cathode centre. That is, each plume emerging from a spherical cathode aperture has its mirror image on the other side of the cathode through the cathode centre. Similarly, diverging energetic neutrals have also been shown[8,14] to emerge from a cylindrically symmetric cathode, where the plumes were along the cylinder axis. Again, the plume on one side of the cylinder has its mirror image on the other side, resulting in two neutral beams of equal neutral atom flux but in opposite directions. Thus resulting in a zero net thrust. We have found that closing the cylinder at one end drastically reduces the density of the plume to the point where it was not visible.

In this paper, we report on an asymmetric hollow cathode discharge arrangement that resulted in a unidirectional plume, and consequently a net thrust. Moreover, the plume did not require a neutralizing element since it consisted of energetic neutrals produced by charge exchange collisions within the cathode.

We present results of the energy and flow direction of the energetic neutrals in the plume measured by Doppler shift spectroscopy.

II. Apparatus and Procedures

The plume was made unidirectional by making the hollow cathode asymmetrical as shown in figure 1. It

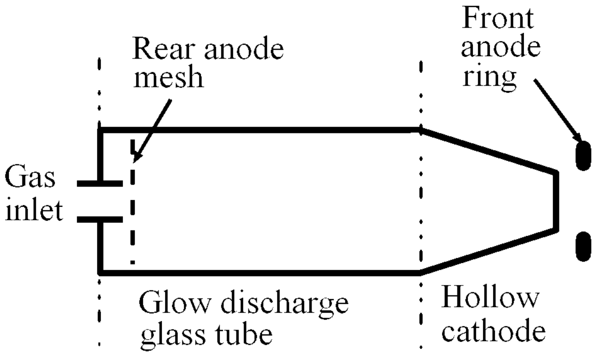

Figure 1. The Charge Exchange Thruster (CXT)

is a linear system with an anode on either side of a conical hollow cathode. The narrow end of the hollow cathode forms the nozzle of the thruster. The wide end of the cathode was at one end of a glass glow discharge tube, which had an anode mesh on the other end. A small gas feed port was placed behind this mesh and allowed hydrogen gas to enter into the discharge tube. A ring anode was required outside the narrow end of the cathode to attract the electrons created within it. It was found that this was necessary for the plume of energetic neutrals to emerge from this end. A possible reason for this would be to ensure a sufficient loss rate of electrons from within the cathode so that the potential hill can be maintained and not neutralized; otherwise there will be a higher density of electrons at the front exit of the cathode leading to a higher electron density at the cathode centre. Further work needs to be carried out to fully understand the effect of electron motion on the resulting discharge. The anode ring could be removed while still maintaining the plume provided that the vacuum chamber in which the thruster is mounted was also at the anode potential. Naturally, the anode ring would be necessary in a space environment. A picture of the operating thruster is given in figure 2

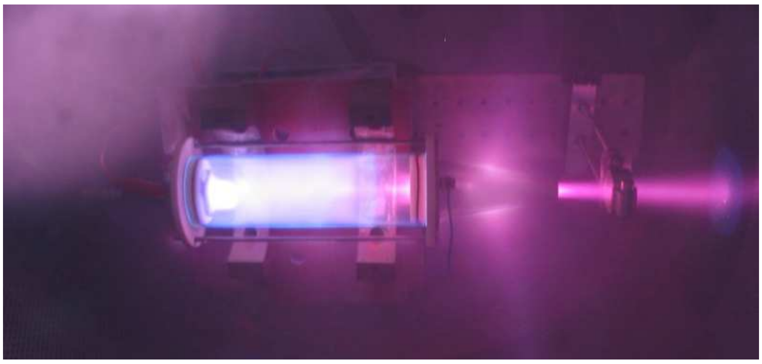

Figure 2. A picture of the operating thruster

The thruster was mounted in a vacuum system that consisted of a bell jar mounted on top of a cylindrical stainless steel vessel. The bell jar was 450 mm in diameter and 750 mm in height. The stainless steel vessel was 450 mm in diameter and 550 mm in height. This vessel was coupled to a 500 L/s turbo-molecular pump backed by a rotary pump. The thruster was mounted in the bell jar section of the chamber just above the stainless steel vessel. Hydrogen gas was fed directly into the thruster at a flow rate of 45 sccm. It was not possible to monitor the pressure within the thruster, however, we studied the dependence of the breakdown voltages on pressure of the thruster before it was assembled as a self contained unit. Achieving breakdown at 4 kV indicated that the pressure inside the thruster was 30 ± 10 millitorr.

The size of the vacuum chamber and the pumping speed only permitted a chamber pressure of 5 millitorr outside the thruster, which is at least two orders of magnitude greater than that of a space environment. However, the results presented here are unlikely to change significantly in such an environment since the ejection of neutrals occurs from a potential hill created within the thruster. The only connection to the external environment is the requirement that electrons be removed at sufficient flux in order to maintain the potential hill. A reduction of outside pressure can only improve this situation since no ions will be created outside the nozzle to reduce the electron accelerating potential. Moreover, the ionization cross-section for electron energies of the order of a keV is less than 0.5×10^{-16} cm^2,[9] which at 5 millitorr gives a mean free path greater than the size of our vacuum vessel so no significant ionization outside the thruster occurred.

The conical hollow cathode had diameters of 9 mm and 60 mm at the narrow and wide ends, respectively. Its length was 80 mm, while the length of the glass discharge tube was 150 mm. It was found that these dimensions were not critical to the production of energetic neutrals in the plume provided a discharge could be maintained in the tube.

The velocity of the hydrogen neutrals was determined using Doppler spectroscopy of the H_α Balmer line of hydrogen (656.3 nm). A Schematic diagram of the optical detection set-up is shown in figure 3. The H_α was detected with an intensified linear diode array (EG&G 1421) mounted on a 0.5 m focal length

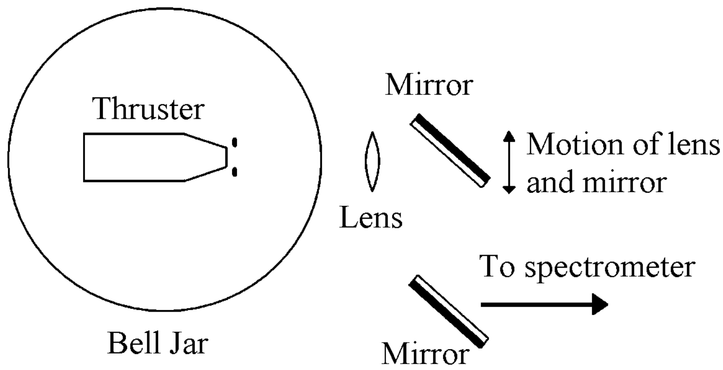

Figure 3. Plan view of the optical detection setup for Doppler spectroscopy.

monochromator (Spex 500M). The resolution of the spectrometer was 0.05 nm. The line of sight of the monochromator was coincident with the axis of symmetry of the cathode, and therefore, with the axis of the plume. That is, the plume was directed towards the entrance slit of the monochromator. This enabled the determination of the velocity distribution of the energetic neutrals.

From Eq. 1 it can be seen that the resulting energetic neutrals originate from different precursor ions. Each precursor ionic specie has the same net charge but has a different mass, and is therefore expected to have a different velocity when subjected to the same electric field. The energy of the precursor ions partitions equally between all of its H atoms[15] and, as a result, the magnitude of excited neutral velocities is different for each of the reactions in Eq. 1. This implies that Doppler spectra should exhibit three peaks, each representing the fast neutral resulting from each of the precursor ions. These three peaks have been measured[16] provided the precursor ions are monoenergetic, which occurs at a lower pressure range than the one we will report on here. As a result, some broadening and structure results in the Doppler shifted spectrum.

III. Results and Discussion

Figure 4 shows the spectrum of the H_α line when the plume is directed towards the monochromator ($\theta = 0$). The narrow line at 656.3 nm is the unshifted hydrogen H_α line. The broad peak to the left of this line is the Doppler shifted H_α from the energetic neutrals in the plume. This line is broadened by the spread in velocities of the energetic neutrals arising from different precursor ions as discussed above. As a result,

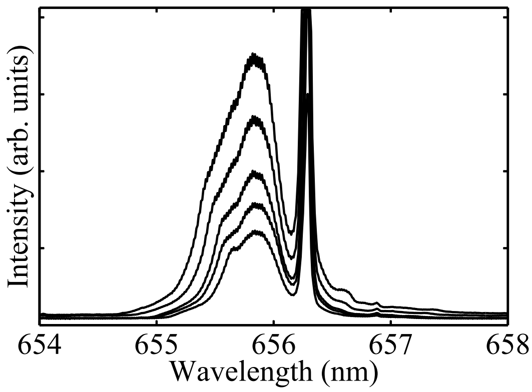

Figure 4. Doppler Spectroscopy of the Exit Nozzle of the CXT for increasing voltages (and currents) across the discharge. The voltages (and currents) from the lowest to the highest intensity Doppler shifted spectra are 4.01 kV (10 mA), 4.85 kV (15 mA), 5.01 kV (20 mA), 6.14 kV (31 mA), and 7.15 kV (45 mA), respectively.

some structure is visible in this broadened peak. The smaller wavelength of the shifted peak (known as a blue shift) indicates that the neutrals in the plume exit the narrow end of the thruster and travel towards the monochromator. Note that we do not see neutrals traveling in the opposite direction since this would result in Doppler shifted wavelengths greater than the unshifted line (known as a red shift). The superimposed spectra in figure 4 represent successively increasing voltages and current across the discharge (indicated in the figure caption) where the increasing intensity represents a higher density of neutral atoms. Moreover, an increasing voltage also results in a higher average velocity. Using Eq. 2 we determined the average velocity to be $\approx 3 \times 10^5$ m/s, with a range of velocities of $1 \times 10^5 - 5 \times 10^5$ m/s. This gives a specific impulse of 3×10^4 s (from the average velocity).

Langmuir probe measurements on a similar hollow cathode discharge[13] have shown that ion densities within the cathode reach values of the order of $n \approx 10^{10}$ cm^{-3}. Assuming this is the density of the exiting neutrals, resulting from the charge exchange of these ions, we estimate the thrust, F_T, (with an order of magnitude accuracy) for the powers used here, to be

$$F_T = nmv^2 A \approx 10^2 \mu N \quad (3)$$

where m is the mass of the hydrogen atom, v is the average speed of the neutrals (3×10^5 m/s), and A is the area of the nozzle exit. As a result, the efficiency, η, of this thruster can be approximated using

$$\eta = \frac{F_T v}{\text{Power in}} \quad (4)$$

which is $\approx$ 75% at 4 kV and 10 mA. However, this does not take into account the loss of gas that did not take part in the discharge, which may result in a much lower effective efficiency. Nevertheless, further measurements need to be carried out in order to determine the actual neutral density, for this hollow cathode arrangement, and the powers that were used to generate the discharge. The previous measurements using langmuir probes were carried out at only 2 kV with a current of about 1 mA. In order to obtain an optimistic upper limit on the thrust we assume that the energetic neutral density has increased by an order of magnitude by an increase of power by an order of magnitude, thus resulting in a density of ($\approx 10^{11}$ cm^{-3}). As a result, it can be expected that the thrust will be an order of magnitude higher ($\approx$ 1 mN) than the calculation given above, for increased power and thruster size. This optimistic upper limit on thrust remains to be tested.

To confirm that the energetic neutrals were originating from within the cathode we also examined the Doppler spectrum from the rear of the thruster, shown in figure 5. However, in this case the axis of the thruster was placed at an angle of $\approx 30°$ so that spatial resolution of the spectra could be obtained. The spectra were recorded from the glow discharge region just outside of the cathode, at the edge of the cathode, and inside the centre of the cathode. Note that there is only a significant Doppler shift at the centre of the cathode, indicating that the largest acceleration is taking place there. Moreover, the Doppler shift is red-shifted indicating that the ions are moving away from the spectrometer towards the narrow exit of the cathode, which is consistent with the blue-shifted spectra taken from the other side.

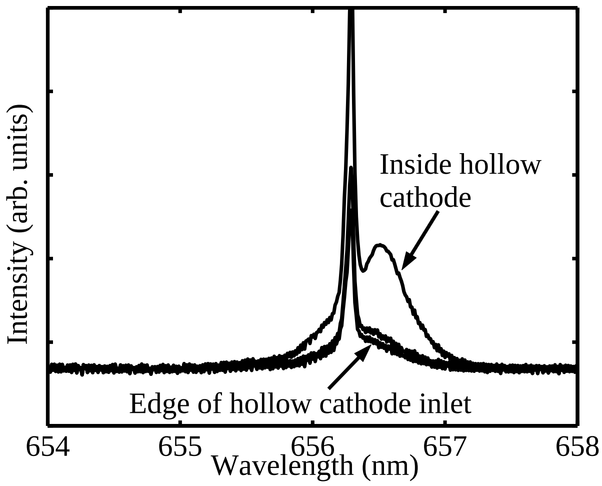

Figure 5. Doppler Spectroscopy of the inlet side of the hollow cathode showing the red Doppler shift within the centre (higher intensity) and edge (lower intensity) of the cathode. The Doppler shift outside of the inlet side (within the discharge) is also shown but almost coincides with the spectrum from the cathode edge.

IV. Conclusion

A new thruster concept, that uses a hollow cathode discharge has been shown to produce a high velocity neutral hydrogen beam ($\approx 3 \times 10^5$ m/s) for powers in the order of 10^2 W. In particular, a conical hollow cathode, which is part of a DC discharge, formed the nozzle. Using Doppler spectroscopy, it was shown that the high velocity neutrals originate in the cathode centre and are accelerated outwards. It was suggested that this is due to ions that originate at the centre of the cathode and accelerate outwards due to a potential hill within the hollow cathode discharge. These ions then become energetic neutrals due to charge exchange with the background gas, and exit the thruster as a collimated beam of energetic neutral atoms. This circumvents the need for accelerating grids and a separate neutralizing source and therefore reducing the design complexity and potentially increasing the efficiency of the thruster. The reduced complexity has the potential to offer increased lifetime and thrust density. An estimate of a thrust of $\approx 10^2$ μN at powers in the order of 10^2 W was obtained based on plasma density measurements on a similar discharge and the velocities obtained from Doppler spectroscopy on the thruster presented here. An optimistic estimate of thrust of ≈ 1 mN was made for increased input power in the order of 10^3 W.

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