Plasma Diagnostics of Miniaturised DC Glow Discharge Thruster Concept

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Abstract. The DC discharge microthruster concept is a simple, energy efficient plasma micropropulsion system that operates using an ionisation-acceleration coupling mechanism. It was developed in the hopes of addressing some of the shortcomings of many state-of-the art electric micropropulsion systems. In this paper, measurements of the thruster's extracted ion beam current as a function of electrode aperture number are presented. The results are compared with theoretical predictions and then used to obtain estimates of the system's thrust. The paper concludes with a discussion of the system's overall efficiency based on its estimated thrust per unit of input power.

1. Introduction

Electric propulsion systems have seen much success on large satellites due to their low fuel consumption and high overall efficiencies [1]. Attempts to miniaturise these systems for applications on the small satellite platform have been physically prohibited since many of them are not scale invariant. Furthermore, power and mass budget restrictions imposed on small satellites creates an additional barrier for the implementation of propulsive mechanisms on these systems [2]. The proposed micropropulsion concept presented here draws inspiration from the popular Direct Current (DC) glow discharge tube [3]. It utilises an ionisation-acceleration coupling mechanism which eradicates the need for additional components and thus reduces the overall size and mass of the system in alignment with the constraints imposed on the CubeSat platform [4]. Additionally, different discharge regimes are obtainable by varying the potential applied between the system's electrodes. These discharge regimes would allow for various operating modes on a potential thruster leading to a system with a high versatility [5].

2. Theoretical Background

The thruster concept studied here can be viewed as a quintessential ion source consisting of a plasma and an accelerator (more commonly called an extractor). The plasma is produced through the electrical breakdown of a gas between an anode and a cathode, with the cathode acting as the ion accelerator/extractor in this context. The ions produced from the plasma flow towards the extractor, where a fraction of them are ejected out of the system through a single or multiple apertures, producing an energetic ion beam. A high voltage power supply provides the means for biasing the plasma. This power supply can also be called the accelerator supply as it determines the ion acceleration voltage V_a [6]. The anode is biased with the positive high voltage, while the cathode is fixed at ground potential. The resulting electric field between the electrodes acts as the acceleration mechanism allowing the ions to flow to the extractor. Figure 1 illustrates this concept.

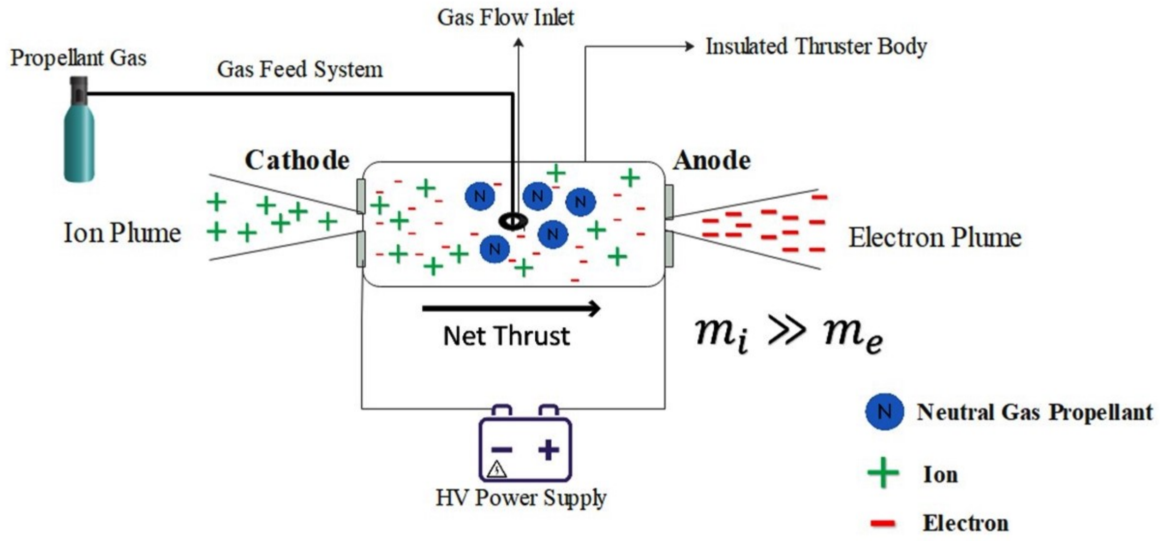

Figure 1. Schematic of the thruster concept. The cathode extracts the positive ions into a focused beam which creates a net momentum providing the desired thrust.

The net thrust T generated by the system can be deduced from the acceleration voltage V_a, and the ion current in the extracted beam I_b as follows [1]:

$$T = \gamma\sqrt{\frac{2MV_a}{e}}I_b \tag{1}$$

Where, M is the ion mass, e is the electronic charge and γ is the thrust correction factor-which accounts for the presence of doubly charged ions within the beam, along with thrust dissapation due to beam divergence [1].

In a cylindrically-symmetric extraction system, the total extracted ion beam current can be calculated from the Child-Langmuir Law as follows [6]:

$$I_b = I_{CL} = \frac{4}{9}\pi\epsilon_0\sqrt{\frac{2e}{M}}S^2V_a^{3/2} \tag{2}$$

Equation (2) holds if the ion beam current is space charge limited and the emission area is planar and infinte [6]. Here, ϵ_0 represents vacuum permitivity. The aspect ratio S is defined as the ratio of the aperture radius to the discharge gap (distance between the electrodes) i.e, $S = r/d$. Then, for a fixed aspect ratio the extractable ion beam current will be proportional to the acceleration voltage to the three half power (i.e. $I_b \propto V_a^{3/2}$). The remaining constant of proportionality is called the perveance of the extraction system [6].

Many satellite missions implement orbital maneuvers which require an appreciable amount of thrust to be produced at set periods of time. In these situations, it is important optimize thrust production. This can be accomplished by adding additional apertures to the extractor electrode. However, the addition of apertures will decrease the total electrode surface area and subsequently decrease the secondary electron emission rate. Thus a higher acceleration voltage, relative to a single aperture system, will be required to generate a particular discharge current.

3. Experimental Setup

The thruster body was constructed from high temperature resistant speciality ceramic material to mitigate any undesirable effects when coming into contact with the discharge plasma. High purity (99.99%) argon was used as the working gas (propellant) for all experimental tests while high durabilty stainless steel was selected as the electrode material.

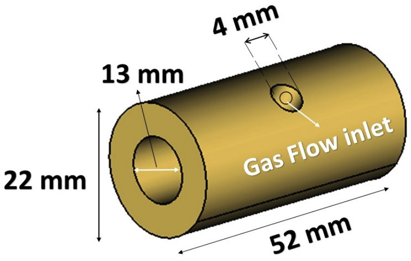

Figure 2. Ceramic thruster tube geometry.

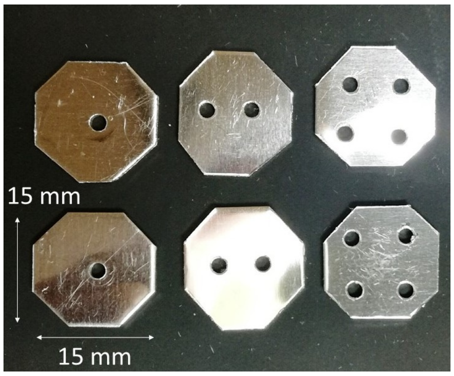

Figure 3. Different electrode aperture configurations explored: 1x2mm, 2x2mm and 4x2mm apertures.

The thruster needed to be small enough to meet the size constraints of small satellites, it also had to have a sufficiently large opening to facilitate the addition of apertures on the electrode surfaces. A length of 52 mm and inner diametre of 13 mm was found to be appropriate to meet these requirements. Additionally, a 4 mm nylon thread was securely fitted at the gas inlet opening and was used to connect a plastic tube from which propellant gas was fed into the thruster. The electrodes were attached to the open ends of the tube using a vacuum compatible adhesive. Extreme care was taken to ensure that the apertures were symmetrically aligned with each other on both ends of the thruster. The experiments were conducted using three different electrode aperture configurations (see figure 3).

4. Methodology

Figure 4 shows the general experimental setup. A 760 mm diameter x 200 mm high stainless steel ring vacuum chamber, fitted with multiple access ports, was used to simulate the ambient space environment. The chamber was pumped down to $5 \pm 1 \times 10^{-5}$ torr with the aid of an Alcatel 2012A roughing pump and a Leybold-Haraeus water cooled diffusion pump. An in-house developed mass flow measurement system, based on the orifice plate concept, was used to measure the mass flow rate of the propellant gas into the thruster (refer to [7], p.63-79 for more details on the procedure used). Mass flows as low as 10^{-7} kg/s were accurately measured using this procedure. In these experiments the mass flow rate was kept fixed at 180 ± 4 ng/s. The HV power supply was then switched on and the current was set to 1 mA.

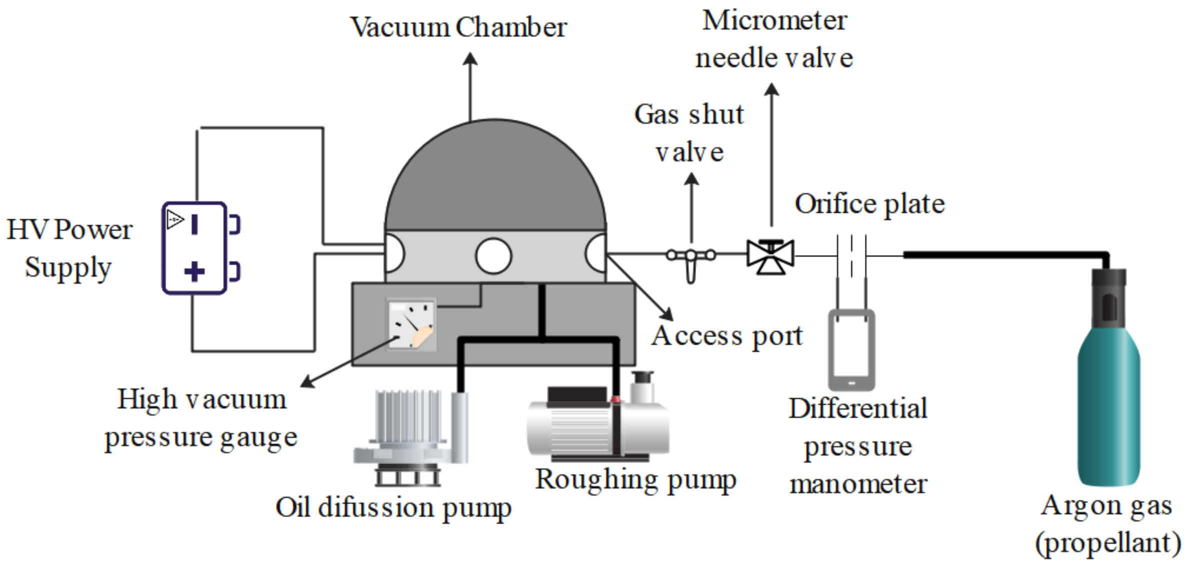

Figure 4. Schematic of the general experimental setup (outside of the vacuum chamber).

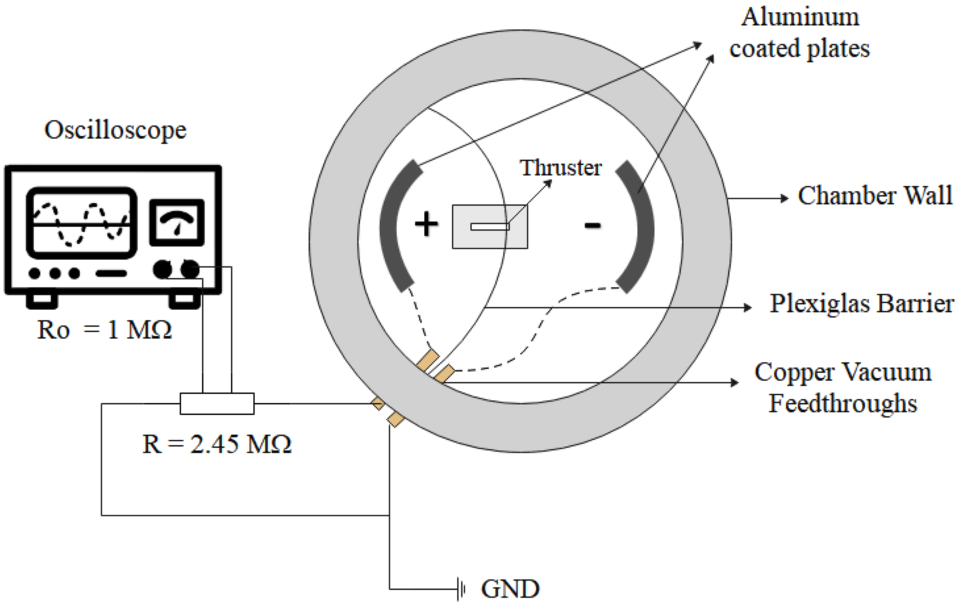

Figure 5. Schematic of the extracted ion beam current measurement setup (inside the vacuum chamber).

Figure 5 shows the experimental setup on the inside of the vacuum chamber. The electrodes on each end of the thruster were connected to the HV power supply with high voltage cables through copper vacuum feedthroughs. Two aluminum coated mylar sheets were used as collector plates to measure the extracted ion beam current. The plates were positioned 90 ±10 mm and 180 ±10 mm from the cathode and anode respectively and were separated by a plexiglas barrier. The plate at the anode end was connected directly to ground, while the ion beam collecting plate was connected to a 2.45 ±0.01 MΩ terminating resitor and then to ground. An oscilloscope, with internal impeadance of 1 MΩ, was used to measure the voltage drop across the resistor. The osciloscope measured the average plate voltage over 60 seconds and, from this voltage, the beam current was deduced through Ohm's law. Multiple trials were conducted for averaging and to check for repeatibility.

5. Results and Discussion

The measured extracted ion beam current for a single, double and quadruple 2 mm aperture electrode configuration is shown in table 1 (the theoretically predicted ion beam currents, for multiple apertures, according to the Child-Langmuir law is given by I_b^{CL}). In each case, the discharge current was kept fixed at 1 mA for comparison. The acceleration voltage V_a corresponding to the 1 mA discharge current, for each aperture configuration, was obtianed from the LCD display panel on the power supply and ranged from 1.5 ±0.1 to 3.5 ± 0.1 kV. Ion beam currents on the order of tens to hundreds of microamps were measured from which the system's thrust was calculated using equation 1. Note however, that the thrust calculated in table 1 does not take into account the correction factor γ and is therefore only an estimate of the system's actual thrust. This is justified since the beam divergence angle, calculated from the spot size of the beam at the collector plate, was measured to be less than 0.2 rad. Thus, the thrust correction factor can be taken as unity to good approximation.

The results show that for a fixed aperture diametre of 2 mm and a discharge current of 1 mA, increasing the number of apertures increases the total extracted ion beam current as expected. However, the results obtained do not match the Child-Langmuir law and suggest that the ion beam current is much greater than theoretically predicted. A possible reason for the discrepancy is that the current measured at the plate may not be the same as the total current leaving the thruster. As noted by Brown I G 2004, the measurement of the ion beam current is affected by the presence of secondary electrons genereated from ion impacts on the collector plate as well as the presence of ambient neutral gas particles along the beam path [6]. Collisions between the various particle species may have generated the excess ion current observed.

Table 1. The relationship between the number of apertures, the average ion acceleration voltage, the measured ion beam current (from the 2.45 MΩ resistor) and the estimated thrust for a fixed aperture radius of 2 mm. The discharge current was kept constant at 1 mA across all aperture configurations.

Aperture No.	V_a (V)	δV_a (V)	I_b (μA)	δI_b (μA)	T (μN)	δT (μN)
1	1765	±10	10.29	± 0.15	0.13	±0.02
2	2340	±10	102.98	± 1.45	1.43	±0.12
4	3435	±10	135.79	± 1.91	2.29	±0.13

One may naively expect the "thrust" to increase linearly with the number of apertures, but the system is likely much more complex. These early results seem to indicate that the apertures "interact" non-trivially with each other. The experiments need to be repeated more carefully with a more sophisticated setup. Moreover, it is recommended that a much larger sample size of apertures is studied, with aperture numbers ranging from 1 to > 20, in order to make a pattern more apparent. Addtionally, one can also experiment with changes in the aperture size to identify the optimal input parameters (current, voltage etc.) for a specific aperture configuration.

6. Conclusion

Ion beam current measurements were conducted on the DC discharge based microthruster. These measurements were used to obtain estimates of the system's thrust. The measured ion current was found to be in excess of the theoretical prediction by the Child-Langmuir equation. This discrepancy may be attributed to a non-ideal experimental setup i.e. the measurement of the ion beam current may have been affected by the presence of secondary electrons genereated from ion impacts on the collector plate as well as the presence of ambient neutral gas particles along the beam path. It will therefore be necessary to use a more sophisticated measuring apparatus (for example, a Faraday cup probe) to make more accurate measurements of the ion beam current. Nevertheless, this experiment has verified that a microthruster based on an ionisation-acceleration coupling mechanism can work in principle and can produce a thrust ranging from 0.13 ± 0.02 μN to 2.29 ± 0.13 μN depending on the number of extraction apertures used. It must be noted that the addition of multiple apertures introduces a thrust efficiency trade-off and based on the data from these experiments it may be more beneficial to use a 2x2 mm extractor aperture configuration for optimum thruster performance under these conditions. The main purpose of these experiments, namely to determine thrust production with various electrode apertures, was successfully demonstrated. The results of this paper will justify a more in depth investigation.

Acknowledgements

The financial assistance of the National Research Foundation (NRF) towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the lead author (Mr. Maheen Parbhoo) and are not necessarily to be attributed to the NRF.

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