Introduction of a miniaturized Hall Effect type thruster

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Abstract. Electric thrusters for satellites and space probes are amongst the most efficient propulsion systems, but are difficult to miniaturise. A concept for a miniaturised thrusters is presented, which, in operation, most closely resembles a Hall Effect thruster without a magnetic field. The thruster consists of a hollow tube with a strong homogeneous electric field inside it, parallel to the tube walls. Neutral gaseous propellant is allowed to flow through the tube, where ionisation occurs via electric discharge, accelerating the ions and electrons in opposite directions. Three possible modes of operation are presented. The continuous discharge mode is examined in more detail, and a comparison between a complete and incomplete ionising system is made. The system showing incomplete ionisation could be engineered to function more efficiently. Some observations from preliminary tests are presented.

1. Introduction

The new, more compact designs for space craft tend towards miniaturization of its components [1]. Advantages of using smaller components include economic factors, such as smaller material and launch cost, but also improved versatility of the probes or satellites [2]. Use of smaller spacecrafts will require smaller propulsion systems. Amongst the most efficient propulsion units are electric systems, such as the gridded ion engine, the FEEP and the Hall Effect thrusters [3]. Numerous other designs exist, but are usually inferior in performance [2]. Each of these technologies is mature, and over the course of development has acquired a characteristic size. The size of the gridded ion engine is restricted by the size of its ionisation chamber, a reduction of which will detrimentally affect performance [4]. The Hall Effect thruster can be built smaller, but still relies on a strong, heavy magnet to circulate electrons for efficient ionisation of the propellant. The FEEP can be built as small as ~1kg [5], but has its own problems [2].

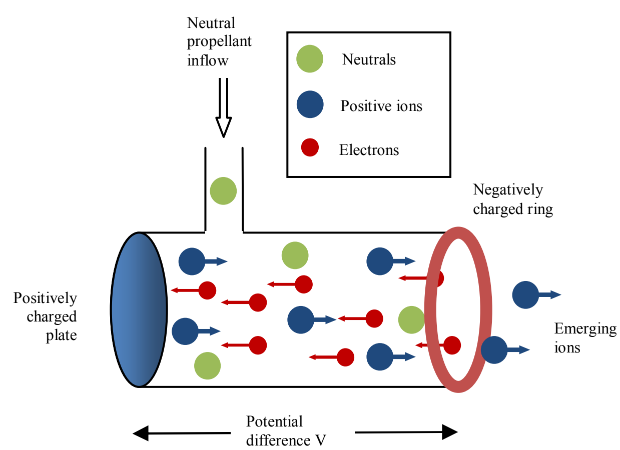

Figure 1. Schematic of miniaturised Hall Effect type thruster

We introduce a simple configuration which most closely resembles the Hall Effect thrusters without the magnet (figure 1). A strong field is created inside a tube, by an anode plate on one end and an cathode ring on the other, through which the neutral propellant flows. The strong field ionises some of the propellant, which in turn will lead to a Townsend avalanche type effect: electrons will be accelerated towards the anode, ionising more neutrals, while ions will accelerate towards the ring and be ejected. An external mechanism such as a hot cathode or plasma bridge must be included in the final design for neutralisation of the emerging plume.

2. Modes of operation

We consider three modes of operation.

2.1 Breakdown mode

This mode operates in a pulse fashion. Gas is injected into the tube chamber and a large voltage is applied suddenly. A complete breakdown of the gas occurs inside the tube, such as is the case in a spark discharge. All the gas in the volume is ionized, the electrons being collected at the plate and the ions ejected at high speeds. This mechanism has been observed during initial tests. Such a mechanism would have to be carefully timed, so that the gas flow and discharge are synchronized and no gas is wasted. Potential advantages of such a system include that a reasonably large impulse can be imparted on the craft quickly, and that it need not run in continuous operation, eliminating some thermal concerns.

2.2 Open mode

This mode has not been tested and is only theoretical to date. Here, both the anode and cathode are rings, and that the propellant is ionized via the same mechanism as outlined above, but here the electrons are immediately emitted out of the tube and away from the craft. Since the ions are much more massive, momentum will be imparted predominantly by their movement. Advantages of such a system include immediate neutralization, if the electrons are forced towards the ions, and minimization of components.

2.3 Sustained discharge mode

In this mode parameters such as gas density, accelerating potential and tube dimensions are chosen such that a partial sustained discharge occurs inside the tube, which is continuous. The discharge is sustained by an externally stimulated electron current, originating either from ion impact on the ring, photoelectrons ejected by UV light from the rings, the external hot cathode/plasma bridge or even a small radioactive source inside the tube. This mode has also been observed during initial testing, and data was collected (see section 4). It is noteworthy that in this mode, incomplete ionization of the propellant gas inside the tube is likely. A more detailed view of this is presented next.

3. Effects of incomplete ionisation

In conventional electric propulsion systems, propellant utilization is strongly related to ionization efficiency of the propellant. In gridded ion engines, for instance, neutral propellant atoms exiting

through the grid can collide with fast ions, and be redirected against the grid causing erosion which affects the engine life [6]. Usually, a high degree of ionization is desired.
I now outline a scenario in which ionization is incomplete, but propellant utilization is nevertheless high.

Consider two tubes, of length d and cross-sectional area A, see figure 2. Inside and along the tubes is a homogenous electric field generated by a potential difference V. In one tube, called system 1, all the neutral propellant entering the tube is ionised and ejected on the other side with a final velocity which was attained through unimpeded acceleration. In the other tube, called system 2, there is only partial ionisation, and the ions travel on average with some drift velocity due to regular collision with

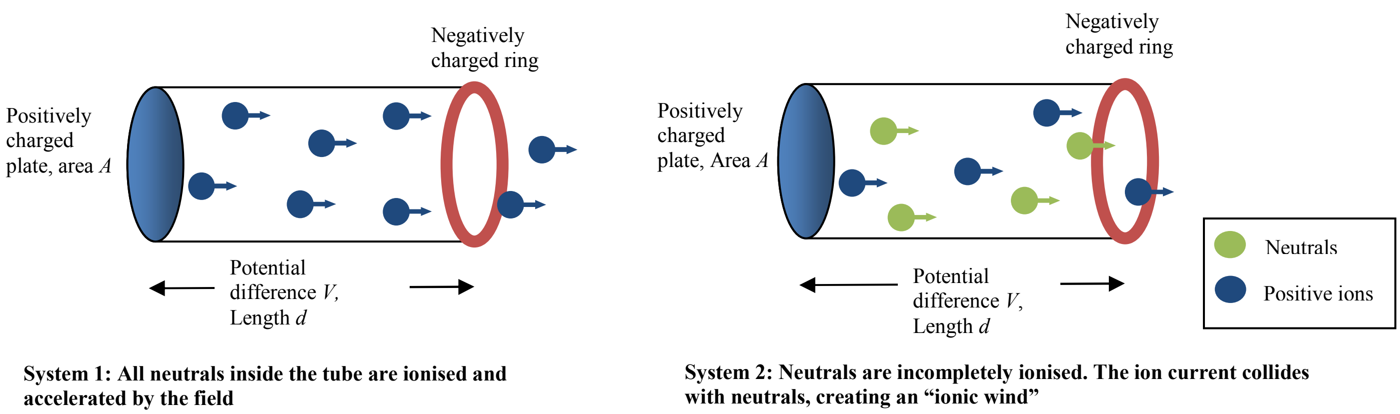

Figure 2. Description of system 1 and system 2, as used in the derivation (see text)

neutrals.
The electrostatic force applied in accelerating the ions is transmitted via the electric field against the tube. We consider a small cross sectional volume of the tube, dV, which contains a number of charges $N.q$, and which exerts a small force against the tube given by $dF = NqE$,

In system 1, the charge movement is unrestricted and charges can be shown to exit with a velocity

$$v = \sqrt{\frac{2Eqx}{M}}.$$

Using the definition of the current and integrating, a force

$$F_1 = i_1 \sqrt{\frac{2V_1 M}{q}}$$

is exterted on the tube, where i_1 is the total ion current, V_1 the potential difference between the ends of the tube and M/q the mass to charge ration of the ions.

For system 2, ion movement is restricted by collision with neutrals and the ions acquire a drift velocity proportional to the square-root of the homogeneous electric field inside the tube, $v = const\,.\sqrt{E}$. Proceeding as before, the force acting on the tube can be calculated to be

$$F_2 = i_2 . \left(\frac{2}{K}\right)^{\frac{1}{4}} . \sqrt{\frac{V_2 M d}{q\lambda}}$$

where i_2 is the current inside the tube, K the momentum transfer fraction between ions and neutrals, and λ the mean free path. The current i_2 is smaller than i_1, if the same number of neutrals flow through the tube.
We next want to ensure that we use the same rate of propellant consumption in both systems. This means that

$$\frac{i_1}{q} = \frac{i_2}{q} + \frac{\dot{m}}{M},$$

the number of charged particles ejected in system 1 is equal to the number of charged particles ejected of system 2 added to the neutrals ejected. It is convinient to rewrite this as

$$\frac{\dot{m}}{M} = s\frac{i_2}{q}$$

and substitute it in the mean free path λ:

$$\lambda = \frac{1}{n\sigma} = \frac{1}{\frac{\dot{m}}{MAv_e}\sigma} = \frac{1}{s\frac{i_2}{q}\frac{1}{Av_e}\sigma} = \frac{qAv_e}{si_2\sigma}$$

In order to have a basis for comparison, the power input must be identical for both systems, $i_1V_1 = i_2V_2$. A comparison between the two systems can now be made at the same propellant consumption and electric power input. This yields a ratio between the forces

$$\frac{F_2}{F_1} = \frac{1}{\sqrt{2}}\sqrt{\frac{s}{(1+s)^2}} . \left(\frac{2}{K}\right)^{\frac{1}{4}} . \sqrt{\frac{\sigma d}{Av_e}}\sqrt{\frac{i_1}{q}} . \qquad [1]$$

The relative size of the thrust, all other parameters being equal, depends on choice of material, propellant, amount by which the propellant ionises, dimensions of the actual thruster as well as operation parameters (v_e and i_1).
When equation [1] >1, system 2 produces more thrust at the same propellant utilisation and power than system 1, within the context of these descriptions.
A maximum F_2/F_1 occurs at $s = 1$, when the number of neutrals equals the number of ejected ions, making the s-dependent ratio = ½.
Hence, thrust produced per power input of an incomplete ionising system can be larger than for a complete ionisation system, depending on engineering factors. Incomplete ionisation is favoured even further since, in the above, ionisation power cost has not been taken into account (which is smaller for system 2). Also, space charge effects are likely to be suppressed due to a smaller ion current.
This section was intended to illustrate that inclusion of ionic wind effects (as occurs in incomplete ionisation) can be beneficial for thruster performance [7].

4. Preliminary measurements

The purpose of the preliminary tests was to confirm that the system is feasible in principle and to obtain some data for the electrical behaviour. Electrical behaviour can be related to the expected thrust. A thruster as shown in figure 1 was constructed, whose tube diameter was 1 mm, and length 4mm. The propellant used was air, after tests using Helium failed. The plates at the end were made of stainless steel, the mass flow rate was 1 mg/s. Background pressure in the chamber was 1.10^{-3} Torr. A neutralisation plate located 4 cm from the tube exit was used to neutralise the ions. The results are shown in figure 3 for two sets of measurements.

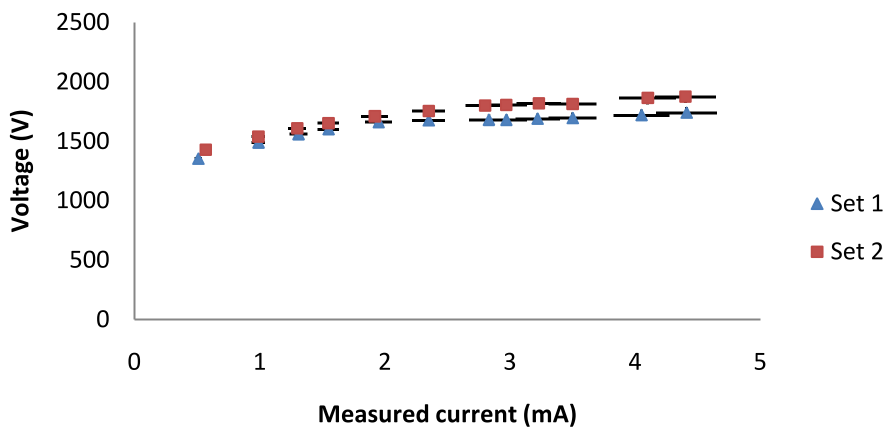

Figure 3. Preliminary electrical data: Current into the thruster was measured against the potential difference between the plate and the ring.

Set 2 was taken with the same unit after set 1. The voltage between the sets increased at the same current and the thrusters failed after about 2 hours of operation. Noticeable was the shallow slope of the data; the voltage did not increase noticeably with current. The onset voltage was recorded to be around 1400 V, however it was necessary to increase the voltage to about 1700V before discharge started, which is likely due to the absence of secondary, current sustaining electrons being created before this voltage. During operation, the voltage and current were quite stable, and a bluish plume (characteristic of air discharge) exiting the tube and spreading was observed.

5. Conclusions

We introduced a mechanism leading to the miniaturization of an electric propulsion system reminiscent of the Hall thruster. Such a system could be of interest for the small satellite and space probes community, since it is envisioned to be light (~grams) and operate at small power levels (~Watts). There are three modes in which the system could operate, two of which (continuous discharge and spark discharge) are potentially possible within the same unit. The continuous discharge mode has been investigated theoretically to some degree. It was shown that there exists a possibility for a system which incompletely ionizes the propellant to have a larger thrust/power ratio at similar propellant consumption. The assumptions made for the model were simplistic, and not applicable for all ranges of parameters. Most serious is the assumption of the form of the drift velocity, which will certainly be affected as soon as ion concentration becomes too high, and ions dominate the plume. A proof of principle unit was built and tested, and the electrical characteristics recorded. A plume was observed, and spread upon exiting, as is common in ion engines. The thruster failed after about 2 hours of operation, and examination showed black residue on the metal parts and inside the tube, indicating oxidization. This is not surprising since air was used as a propellant, and this type of erosion is expected to be absent if a noble gas like Xenon is used instead. Thrust was not tested for, but will be estimated in future from the electrical power dissipation.

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