Characterization of plume and thrust for the corona ionization space propulsion system

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Abstract. The thrust production of a miniaturized space propulsion system using corona ionization of the propellant depends on the exhaust plume composition. A two fluid simulation was constructed to extract electrical properties of the plume, such as the electric field, potential and the ion and electron charge densities. The form of the potential is seen to depend on the propellant flow rate, which affects the non-uniform pressure profile appropriate for this system and hence ion mobility. The form of the pressure profile used introduces a space charge polarization close to the ionising needle, which dramatically increases thrust production. The thrust description, which shows the local thrust contributions from the plume, indicates that thrust can have even negative components in the polarization region, but is overall much larger than for the conventionally studied constant pressure background system.

1. Introduction

Since the launch of SANSA (South African space agency) in 2010, space related activities have received new impetus in southern Africa. Although the emphasis is on astronomy, science and engineering applications are also being pursued. One of the research directions concerns itself with electric propulsion systems (or "thrusters") which can be used in outer space on deep space probes or satellites.

Lately, research on thruster miniaturisation has been gaining in importance, with the aim to reduce production and launch costs. At the same time, manufacture of smaller space components became desirable, so that the overall versatility of space vehicles can be increased.

In miniaturising electric propulsion systems, one aims for the high efficiency and long lifetime of larger systems. This can be difficult to achieve; the well-known gridded electrostatic ion engines, for instance, lose efficiency on reduction of the discharge chamber [1], while some progress with the popular Hall thrusters is made [2] , especially on erosion problems.

A number of alternative miniaturized electric propulsion systems is being studied. Work is pursued on thrusters relying on the ejection of charged particles, such as pulsed plasma thrusters, the FEEP, colloid thrusters, Helicon thrusters, vacuum arc thrusters, micro-particle thrusters, hollow cathode thrusters and many of their derivatives (see [3] for a comprehensive discussion of miniaturised electric propulsion systems). Thrusters are studied relying on heating mechanisms of the propellant [4], such as laser ablation thrusters and arc-jet thrusters [5] or else on interaction with external fields, like the electro-dynamic tethers [6]. Many of these systems are unique candidates for specific mission requirements.

Here, we discuss an aspect of a thruster depending on corona ionisation. Since thrust is produced via electrical interactions between the thruster body and the plume, knowledge of the plume composition is vital.

2. Operation of the corona ionisation thruster

The thruster consists of two hollow needles separated by a short distance with a potential difference between them, and embedded in an insulator (figure 1). A propellant gas escapes into vacuum through the needles. At the needle tips, the gas experiences a strong electric field and corona ionization takes place. Electrons are produced at the negative needle tip, positive ions at the positive needle tip. The charged particles are mostly repelled from the needle they emerge from, with a small fraction forming a plasma bridge, ensuring continuing operation. Less than a percent of gas molecules are corona ionized in the gas, forcing the ions and electrons to move through a dominant neutral gas background.

Experimental data has been collected for such a system and is described in detail elsewhere [7].

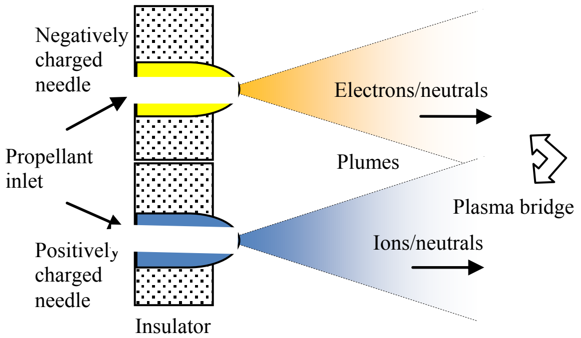

Figure 1. Oppositely charged needles create charged particle flows through a predominantly neutral propellant via corona ionization. A plasma bridge ensures continuing operation.

An analytic model for the radial electric field inside the positive plume was suggested in [7], which made some simplifying assumptions, such as ignoring electrons, using unrealistically large values for the plume spread angle (45 deg) and a very high secondary electron emission coefficient of 0.67.

The similarity in thrust and discharge behaviour of the two needle system of figure 1 and a simpler configuration involving a positively charged needle and a grounded plate (see figure 2) was noted in [7]. The simulation introduced in the next section is based on the simpler configuration of figure 2.

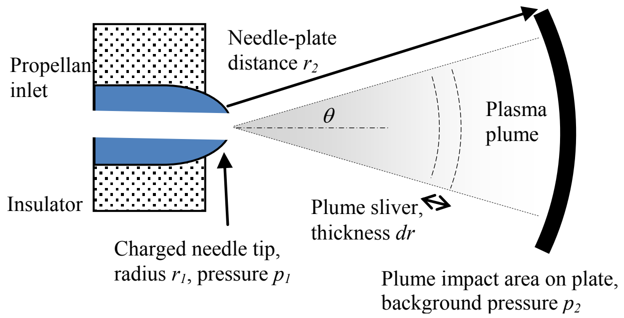

Figure 2. Discharge system of needle to plate configuration showing similar properties to the needle-needle thruster. The gas density of the plume decreases quadratically towards the plate.

3. Two fluid simulation

Non-intrusive direct measurements of plasma systems are difficult to perform on small scales, and analytic solutions of these can often not be found. A simulation can yield valuable insights in such a situation.

We use the well known 1-dimensional two fluid simulation [8] to obtain qualitative insight into the plume behaviour. The simulation considers two concentric spheres with a potential difference and a spatially varying pressure profile (equation (1)) between them. The inner sphere represents the needle-tip and the outer sphere the discharge plate of figure 2. Since the gas expands as a cone into vacuum, an inversely quadratic relationship of the form

$$p(r) = a + \frac{b}{r^2}, \tag{1}$$

was assumed for the pressure decrease as a function of distance r from the needle-tip, as a first approximation [7,8]. Here, the parameters a and b were fixed to satisfy the boundary pressures at the needle tip and the background pressure at the discharge plate. At high potential difference, discharge occurs over the entire enclosed region. We use that fraction of the total current which goes through a cone representing the plume. This conical section is assumed to have uniform density along the angular directions, and besides yielding the measured current, must also satisfy the measured neutral gas flow through it. While more accurate models exist, this model reduces complexity and computational time, and allows direct comparison to the analytical model in [7]. The MATLAB program for this simulation was validated in [8], where all the simulation parameters are also listed.

4. Electric plume composition and propellant flow rate

The discharge occurs between the needle, which emits the propellant gas at a constant mass flow rate, and the discharge plate. In the simulation, their separation was taken as 40 mm with a potential difference of 1000V, and the background pressure was set as 0.6 Torr (these values were chosen because experimental data for them is available [7]). The needle exit pressure varied, simulating a changing flow rate. Experimentally, a flow rate of 1.4 mg/s was close to a needle pressure of 97 Torr, and 1,0 mg/s close to 70 Torr.

The potential, electric field and charge densities for the entire discharge region are shown in figure 3.

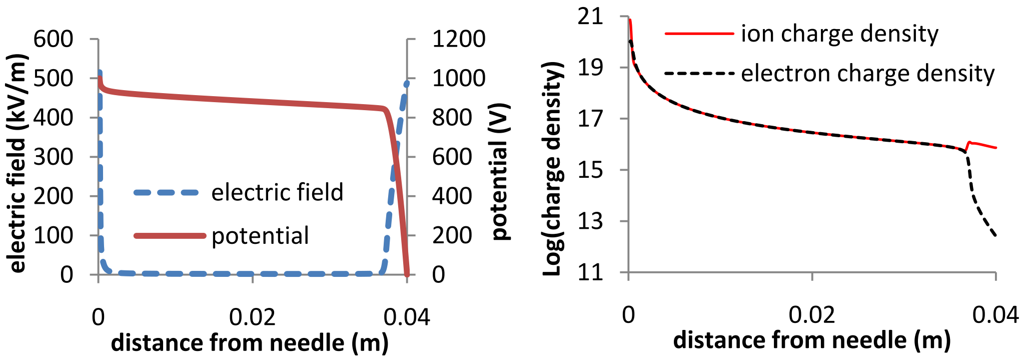

Figure 3. (Left) The potential and electric field throughout the discharge region is shown. (Right) The ion and electron charge distribution (taken for 70 Torr needle tip pressure, representative).

The electric field peaks close to the electrodes (at the anode and cathode sheaths), and is suppressed by the electron presence in between. The potential drops slowly at first, then rapidly within the cathode sheath. The charge densities cancel each other throughout most of the discharge region, except near the electrodes. At the plate, secondary electrons are ejected, accelerated through the gas and give rise to an electron avalanche until the ion charge density is neutralised. We are mainly interested in the region close to the needle, since the plate is an artefact of the simplified system of figure 2.

Figure 4 shows the electric field strength close to the needle for different needle-tip pressures (= mass flow rates). For a needle-tip pressure of 0.6 Torr, the background pressure is constant, and there is no flow from the needle. The field there is suppressed, and similar systems have been studied as ionic wind phenomena. As the flow rate increases, the field increases significantly and a corresponding potential drop occurs close to the needle.

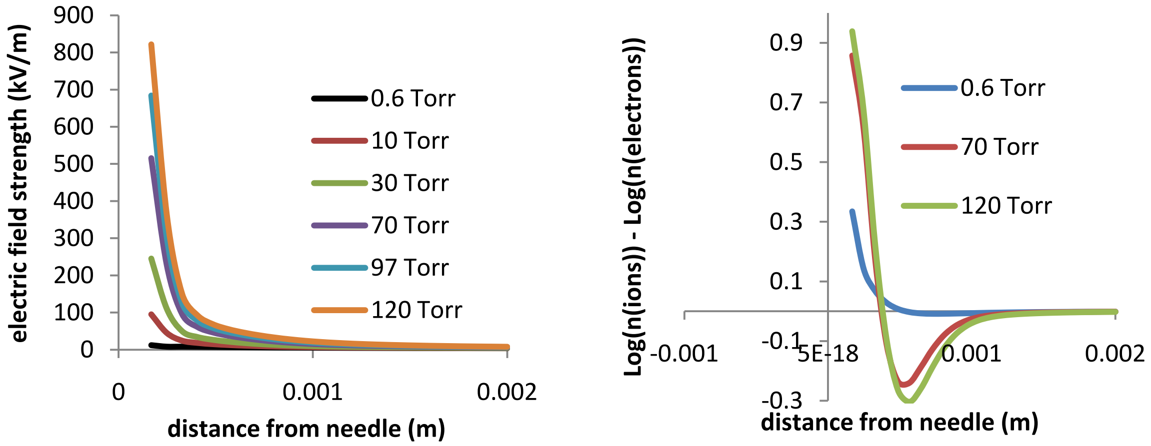

Figure 4. (Left) Electric field strength increases with mass flow rate. (Right) Increased mass flow rate sets up a polarised space charge region.

Figure 4 (right) shows that the decreasing pressure profile of equation 1 introduces a "polarisation" of the space charges close to the needle, which is responsible for the increase in electric field, and which increases with increasing mass flow rate.

5. Thrust characteristics of the plume

The likely origin of thrust for this system is the repulsion of ions in the plume. Other possibilities were investigated [8], but are at best secondary, less important effects. The ions move through the plume with a drift velocity given by a product of their mobility and the electric field, to a good approximation. Both these quantities change throughout the plume (see figure 3(left) for electric field variation and equation (1) for pressure, and hence, mobility variation), giving rise to effective local charge densities, discretised in the simulation by "plume slivers" of thickness dr = 80 microns (see figure 2). These charge densities, which remain constant during discharge once equilibrium has been reached, interact electrostatically with the positively charged needle, exerting a force on it. The force T (= thrust) was shown in [8] to be given by the expression

$$T = \frac{\pi}{2}(1 - cos2\theta) \int_{r_1}^{r_2} q(n_i - n_e)Er^2 dr \qquad (2)$$

where θ is the plume half angle, q is positive electron charge, n_i and n_e are the local ion and electron charge densities respectively, and E is the local electric field magnitude. This information is available from the simulation, and allows us to graph the local thrust contribution from the plume (figure 5).

It is clear that the thrust magnitude responds to the polarization induced by the non-uniform pressure profile of equation (1). The thrust contribution to the total thrust from the region dominated by negative charge density is negative, but despite this, the total thrust increases significantly with propellant mass flow rate, since the positive space charge region more than compensates for this (see table 1).

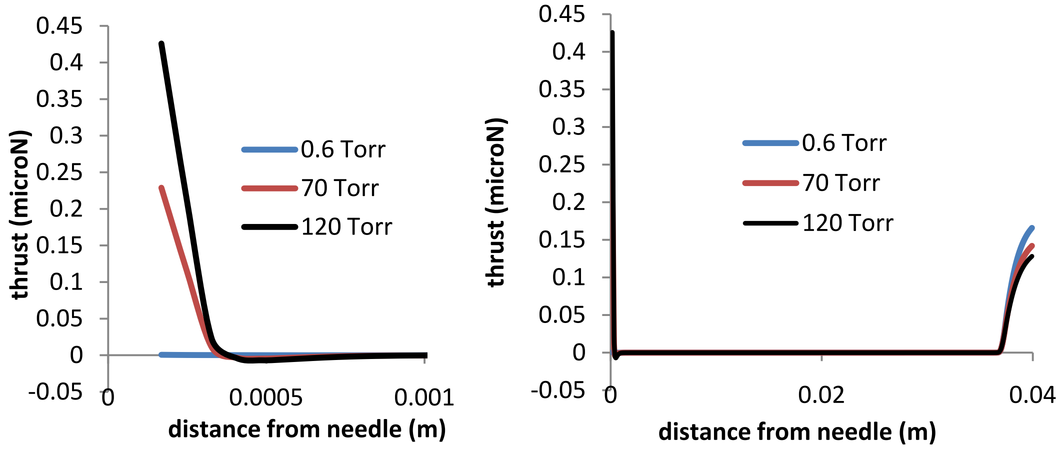

Figure 5. (Left) Thrust contribution from charge densities close to needle tip for three different needle-tip pressures. (Right) Thrust contribution from entire discharge region.

Table 1 shows the global results for the different mass flow rates given by the simulation for a plume angle of ~1.4 degrees, discharge voltage of 1000V and background pressure of 0.6 Torr.

Table 1. Needle tip pressure and simulation results for plume discharge current (= power) and total thrust calculated from equation (2).

Needle-tip pressure (Torr)	Plume discharge current (mA) and Power (W)	Total thrust (μN)
0.6	0.596	8.9×10^{-4}
10	0.581	2.16×10^{-2}
30	0.555	1.07×10^{-1}
70	0.510	3.39×10^{-1}
97	0.483	5.03×10^{-1}
120	0.460	6.35×10^{-1}

The discharge power decreases, while the thrust increases significantly with propellant flow rate. It must be noted that the plume angle is not independent of flow rate, which has not been taken into account here. This will affect the values of the plume discharge current. The variation in discharge current will however be much smaller than the drastic increase (3 orders of magnitude) in total thrust.

6. Conclusion

A two fluid simulation was used to extract electrical properties of the plume, such as the local electric field, potential and charge densities. A variation in needle exit pressure corresponded to different flow rates of propellant being corona ionised. A quadratically decreasing pressure profile, which was chosen to simulate the gas expansion of the plume into vacuum, exhibited increased space charge accumulations close to the needle-tip compared to a constant background pressure environment. These space charges must be a consequence of the higher pressure (= density) close to the needle-tip, which increases ion production rate and decreases mobility. Both positive and negative thrust contributions from the plume were simulated, with the positive contribution far dominating. Thrust was seen to increase drastically with increasing flow rate, with the discharge power varying little. This behaviour will have a large effect on the thruster efficiency and becomes an important design consideration.

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