High thrust over power for electric propulsion

A. Fruchtman and Gennady Makrinich

H.I.T. – Holon Institute of technology, Holon 58102, Israel

Abstract: The momentum delivered by electric force to an ion flow is increased by ion-neutral collisions during the ion acceleration. Measurements show that the momentum increase is proportional to the square-root of number of ion-neutral collisions. The measurements include the (previously reported) measurements of the force exerted by the mixed ion-neutral flow on a balance force meter, and new measurements of the force on the flow along the acceleration channel. The force increase by collisions is considered for use in a high thrust over power thruster and for an all-electric variable thrust thruster.

I. Introduction

A major figure of merit in propulsion in general and in electric propulsion in particular is the thrust per unit of deposited power, the ratio of thrust over power. We have recently demonstrated experimentally and theoretically [1-5] that for a fixed deposited power in the ions, the momentum delivered by the electric force is larger if the accelerated ions collide with neutrals during the acceleration. The higher thrust for given power is achieved for a collisional plasma at the expense of a lower thrust per unit mass flow rate, reflecting what is true in general, that the lower the flow velocity (and the specific impulse) is, the higher the thrust for a given power. This is the usual trade-off between having a large specific impulse and a large thrust. Broadening the range of jet velocities and thrust levels is desirable since there are different propulsion requirements for different space missions. Operation in the collisional regime can be advantageous for certain space missions. In our experiment, the plasma is accelerated by $\vec{J}\times\vec{B}$ force, in a configuration similar to that of Hall thrusters. The thrust enhancement by ion-neutral collisions is therefore under magnetic field pressure in our experiment, and the flow is not charged - limited as it is when thrust is increased by ion-neutral collisions in the case of electric pressure (ionic wind) [6].

In Section II we explain the increase the force and of thrust over power, and describe our experimental results that verify that increase. These results have been described in previous publications [1 - 4]. In Section III we present new results; we describe local measurements of the discharge parameters that allow for the calculation of the electric force on the plasma ions.

II. Ion-neutral collisions and thrust over power

The total electric force at each instant on ions that flow across an accelerating voltage, while they are colliding with neutrals, F_{Ecl}, is

$$F_{Ecl} = F_{Ecs}\sqrt{\frac{a}{2\lambda}} \qquad (1)$$

where F_{Ecs} is the force by a collisionless ion flow,

$$F_{Ecs} = \mathrm{m}_i \Gamma_i v_0 \,. \qquad (2)$$

Here, m_i is the ion mass, Γ_i is the ion flux, $v_0 \equiv \sqrt{2eV_{ac}/\mathrm{m}_i}$, where V_{ac} is the acceleration voltage and e the elementary charge. In the force enhancement factor $\sqrt{a/2\lambda}$, a is the length of the acceleration channel and λ is the mean free path. The expression for the enhanced force also expresses the ratio of force over power. The power deposited in the ions for acceleration is

$$P_i = e\Gamma_i V_{ac}. \qquad (3)$$

The ratio of force over power is therefore

$$\frac{F_{Ecl}}{P_i} = \frac{2}{v_0}\sqrt{\frac{a}{2\lambda}} \qquad (4)$$

A high force (or thrust) over power is important for electric propulsion. This ratio is also increased relative to the collisionless case by $\sqrt{a/2\lambda}$. The derivation of these relationships is described in Refs. [1–4].

The experimental system, composed of a Radial Plasma Source (RPS) and diagnostics, is shown in Fig. 1 and is also described in Refs. [1–5]. Ions are accelerated radially outward by an applied radial electric field, while the radial electron motion inward is impeded by an axial magnetic field.

Measurements of the force exerted by the mixed ion-neutral force on a Balanced Force Meter (BFM) for three different gases and for various gas flow rates and magnetic field intensities are shown in Fig. 2 (from Ref. [4]). The vertical axis shows the values of force over power divided by the square root of mass number M multiplied by the ion-neutral cross section σ. Note that $\lambda = 1/\sigma N$, where N is the neutral gas density. The horizontal axis show the corresponding values of the square root of the ratio of the gas pressure over the accelerating voltage. As is explained in detail in Ref. [4], the high value of Pearson's

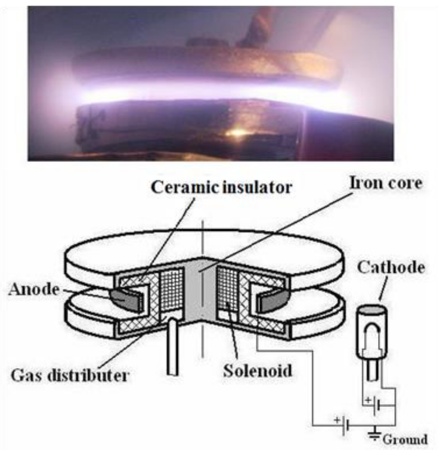

Fig.1: The RPS in operation and a schematic.

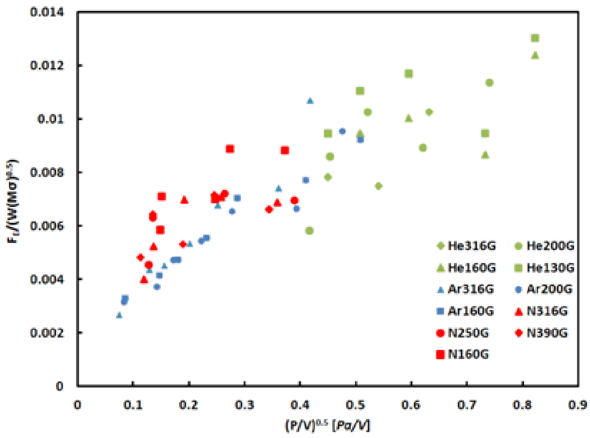

Fig. 2: The force over power normalized to the square root of the product of the ion mass number and the collision cross-section.

correlation coefficient confirms the scaling law suggested by Eq. (4).

In the next section we describe new measurements of the local force on the ions along the acceleration channel.

III. The local electric force on the ions

Figure 3 compares the total electric force on the ions deduced from local measurements to the measured force exerted by the mixed ion-neutral flow. Also is shown the force estimated from measurements by a Balance Force Meter [4].

The total radial electric force on the ions is:

$$F_E = \int_0^a 2\pi b r n e E dr. \qquad (5)$$

Here, n is the ion (plasma) density, E is the radial accelerating electric field, and b is the distance between the disks of the RPS shown in Fig. 1. We measured the n and E at several distances r from the axis, and used these values to calculate approximately the integral to yield the force. The measurements were taken at the middle plane between the disks. The plasma density is expected to be lower nearer to the walls and therefore this calculation overestimates the actual force.

The second curve shows F_{ex}, the force as measured by the Balance Force Meter [4]. The third curve shows the contribution of the plasma pressure to the force. The maximal pressure, nT, is found by local measurements of n and T, the electron temperature. The force due to the plasma pressure is then found as $F_{pl} = (nT)_{max} 2\pi r_{max} b$. Since the plasma

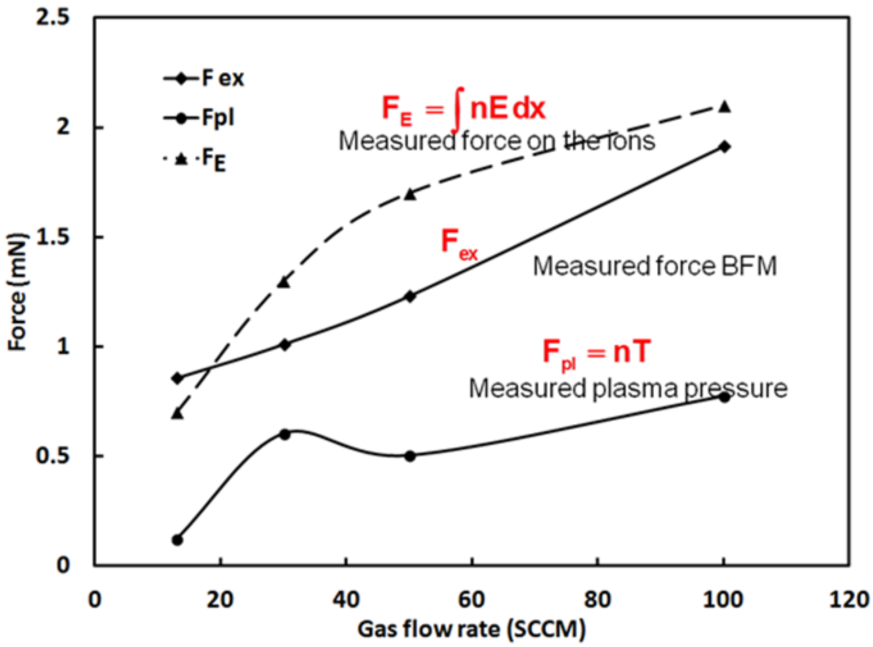

Fig. 3: The electric force and the force due to pressure calculated from local measurements and the measured total force.

pressure is lower nearer to the walls, this expression is also a somewhat overestimate of the force due to the plasma pressure.

The plasma density, the electron temperature, and the plasma potential were measured by use of a Langmuir probe and an emissive probe. We used our analysis of the emissive probe [7].

Figure 3 shows a good agreement between the force exerted by the flow exiting the RPS and the electric force exerted on the ions inside the RPS. The electric force is somewhat larger that the force exerted by the flow, but this can be attributed to the overestimate described above. It is also seen that the force due to the plasma pressure is smaller.

These measurements support our understanding of the forces govern the dynamics of the mixed ion-neutral flow in the RPS. We conclude that the electric forces are not balanced by the plasma pressure. Rather it looks as though, as expected, the electric force is balanced by the magnetic force on the electrons.

Acknowledgments

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