

Preliminary Experimental Evaluation of a Miniaturized Hall Thruster*

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Abstract

A miniaturized 50 W Hall thruster has been designed and manufactured at the Massachusetts Institute of Technology based on the a priori developed scaling model. The thruster has been experimentally tested for operation and the collected data were compared to those for existing larger Argon-operated devices. Qualitative comparison showed good match in performance as well as similarity in general trends. Detailed thrust measurements will be performed to quantitatively assess the microthruster performance to verify the scaling model.

1.0 Introduction

High performance Electric Propulsion is now an accepted part of many new spacecraft designs in the power range of ≈ 1 -10KW. On the other hand, with the exception of low total-impulse, low efficiency PPT devices, no equivalent propulsion technology exist for very small satellites, limited in power to, say, below 100 W. Since most potential microsatellite missions require an on-board propulsion system for orbit maintenance or attitude control maneuvers, miniaturization of the existing propulsion devices is necessary in order to effectively utilize them in the growing microspacecraft world. A Hall thruster, being one of the most mature and extensively tested electric propulsion devices has been chosen for trade studies, design, and manufacturing at a smaller scale.

It is not necessarily true that future practical microthrusters will operate on the same physical principles as successful existing larger thrusters.

On the other hand, it does appear logical to start our search for effective microthrusters by adapting (scaling) those now familiar, so as to highlight potential practical limitations and suggest development avenues. We showed in [1] that, if in fact a few scaling rules can be strictly adhered to, the operating regime, and hence the performance, of the engine can be invariant to scaling. A simplified scaling model was developed based on the physics of the existing larger devices. The scaling model was used to evaluate various thruster configurations, select thruster components and specify the desired performance characteristics. The thruster has been sized for 50 W nominal input power. It was designed, manufactured, and tested in a vacuum chamber at one of the laboratories at the Massachusetts Institute of Technology. Although no conclusive data on the thruster characteristics could be collected due to the lack of a sensitive microbalance, a number of suggestive results were obtained by performing auxiliary measurements. Preliminary assessment and qualitative comparison to the existing larger devices showed good matching as predicted by the scaling relations. Further tests that provide quantitative thrust measurements will determine whether or not the performance of this device is adequate for the intended use on board of the microspacecraft.

2.0 Thruster Design

2.1 Scaling Model

A Russian-built Hall thruster model (SPT-100) was used as a baseline for scaling. This model

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was chosen primarily due to the availability of reliable performance data for various optimal configurations from both experimental and numerical studies. Below is a brief discussion of the scaling laws and their consequences when applied to the design of the miniaturized thruster.

The scaling laws were based on a number of assumptions. Since the specific impulse is often dictated by scale-independent orbital mechanics and mission ΔV requirements, I_{sp} was assumed invariant. In addition, it was assumed that the electron temperature was to remain constant. This assumption is justified by application of an electron energy equation. Since the exhaust velocity and, hence, the specific impulse are both related to the applied voltage, the latter must remain invariant upon scaling. Collisionality properties are preserved by maintaining the ratios between the mean free paths of the species and the thruster dimension. This implies that all the particle densities must scale inversely with the thruster diameter. The mass flow rate and, hence, the thrust of the engine, being proportional to the density and the cross-sectional area, scale linearly with the thruster dimension. Both, the electron and the ion currents scale linearly with length as can be easily verified from the Ohm's law. The utilization efficiency is preserved under these conditions since it scales as the ratio of the ion current to the mass flow rate. The total power input into the thruster is proportional to the current (since the voltage is kept constant), hence it scales linearly with length. This latter result was used to size the thruster, nominally rated for a power of 50 W. The magnetic confinement of the electrons was preserved by maintaining the ratio of the Larmor radius to the thruster dimension. This result indicates that the required magnetic field scales inversely with the thruster dimension, hence becomes larger for small-size devices. Heat fluxes scale inversely with length and grow as well when the size of the thruster is reduced. The two latter results proved to be quite troublesome in the design of the miniature thruster. These difficulties were overcome by appropriately sizing and designing various critical components. Finally, it was shown that under the assumptions and results presented above, all major loss mechanisms scale linearly with power such that the efficiency can be preserved, as desired.

These scaling relations were applied to the SPT-100 model in order to obtain performance estimates for the miniature 50 W thruster. For comparison, some of the representative parameters for the SPT and the 50 W thruster are shown in Table 1. These numbers indicate that the proposed device needs to be extremely small (3.7 mm in diameter), has to provide a magnetic field of 0.5 Tesla, and has to accommodate power fluxes of up to 0.5 kW per square centimeter.

2.2 Thruster Design

Manufacturing of a tiny ceramic insulator, a conventional counterpart to the one used in the SPTs, either by machining or plasma vapor deposition was thought impractical due to the small sizes involved. It was decided to reconfigure the thruster in a fashion similar to that of the existing TAL (Thruster with Anode Layer). In this configuration, the anode was extended towards the exit of the channel leaving a vacuum gap between itself and the magnets. The vacuum gap served as an electrical insulator as well as for protection of the permanent magnets from excessive heating. Although the physics within the ionization zone of the TAL is somewhat different from that of the SPT, the two devices have been observed to be almost identical in performance. Therefore, it was decided to preserve the scaling laws originally developed for an SPT and reconfigure the device as a TAL in order to facilitate manufacturing of the miniaturized components.

Parameter	SPT - 100	mini - SPT
Power, W	1350	50
Thrust, mN	83	3
Isp, sec	1600	1600
Efficiency	50	50
Diameter, mm	100.0	3.7
Flow rate, mg/s	5.0	0.2
Mag. field, T	0.02	0.5

Table 1. Scaled design parameters

It is evident from the scaling relations that the increase in the required magnetic field presents a number of complications from the design standpoint. It can be shown that conventional electric coils of such small dimensions can not be used to produce the required field without

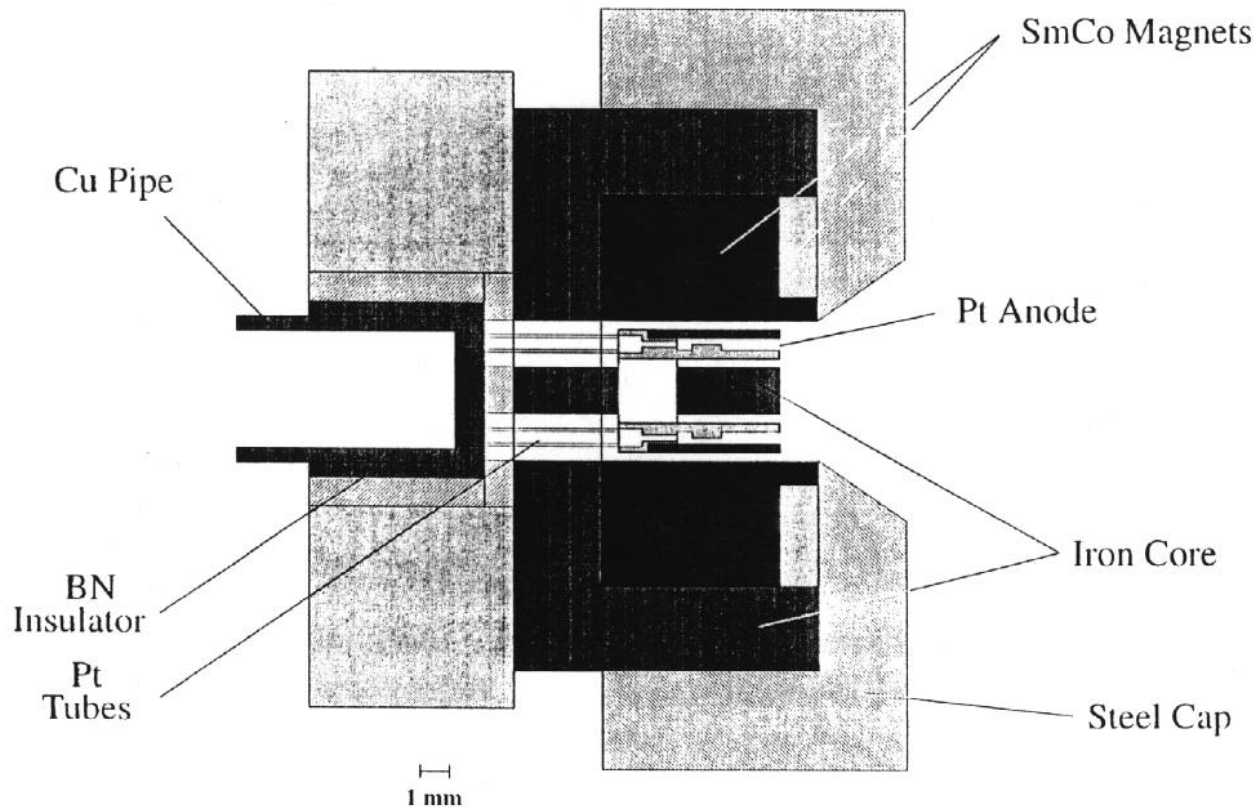


Figure 1. Thruster schematic

overheating. On the other hand, certain permanent alloys in conjunction with a properly sized magnetic circuit are capable of meeting the required specifications provided their temperature can be kept below about 300°C. SmCo alloy was chosen as a suitable material for manufacturing a magnetic circuit with the resultant root-mean-square field value in the gap of 0.5 Tesla.

Thermal design of the thruster was based on dissipation via conductive heat transfer, which dominates at small sizes. Four gas capillaries which deliver propellant to the anode were sized in such a way as to maintain the anode tip temperatures within the allowable limits. Surrounding magnets were thermally connected to a heat reservoir to dump the heat internally radiated from the anode and keep the magnets well below their maximum operating temperatures.

The final version of a miniature thruster is schematically shown in Fig. 1. The anode is designed as a hollow concentric channel with a flow buffer to achieve uniform azimuthal jet distribution. The four platinum capillaries attached to the anode deliver the propellant from the gas distributor region located in the back of the assembly to the plasma channel. The whole anode assembly is fitted and held by a chromated copper disk mounted to the magnetic core in the back. The disk is a structural component which is also used for mounting the thruster to the test rig. The frontal cap (made of stainless steel) is a structural component that presses the magnets and a protective carbon ring together into the iron assembly. The carbon ring is located in front of the main magnet near the opening of the channel (shown dark). It protects the magnet from the high-velocity ions impinging into the walls as they accelerate away from the anode.

3.2 Experimental Results and Evaluation

The thruster has been tested with Argon at various operating conditions. The tank pressure was less than about 6×10^{-4} Torr, equivalent to about 2×10^{-5} Torr in a 1.4kW device. A simple impregnated filament was used as the cathode. Voltage vs. current characteristics were recorded for different mass flow rates. The results are presented in Fig.2.

Although the thruster performance cannot be properly evaluated based solely on this information, some sense of the physical regimes attained can be gained by comparison to Hall thruster data obtained for Argon by other investigators. In particular, we have selected for this purpose the data of Semenkin and Chislov [3] and of Komurasaki, Hirakawa and Arakawa [2]. These were thrusters with somewhat different

geometries and values of the magnetic field-diameter product than our device, so only qualitative agreement is to be expected. We have chosen in our comparisons to ignore the magnetic differences, and to scale the flow rates and currents in proportion to diameter, as in the scaling relationships discussed in Sec. 2.1. In Fig. 3 we have reproduced the Current-Voltage data given in [3], Figure 4, for a range of flow rates from 0.44 cc/s (0.79 mg/s) to 0.9 cc/s (1.61 mg/s), and for pure Argon operation. The thruster used by [3] was a of the TAL type, with a mean diameter of 27 mm. Using for our thruster a mean diameter of 4 mm. we have superimposed on Fig. 3 our results from Fig. 2, with both current and flow rate scaled by the factor $27/4$. We observe first of all that our curve for a scaled flow of 1.33 cc/s is approximately located where one would expect it by extrapolation from the higher flows in the data of Ref. [3]. On the other hand, there is some

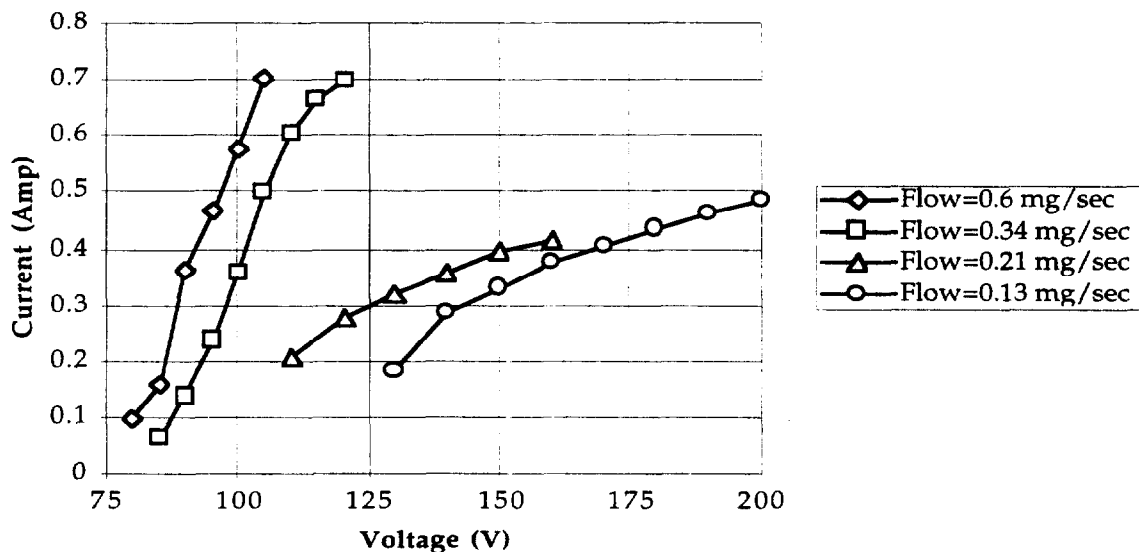


Figure 2. Experimental I-V Characteristics

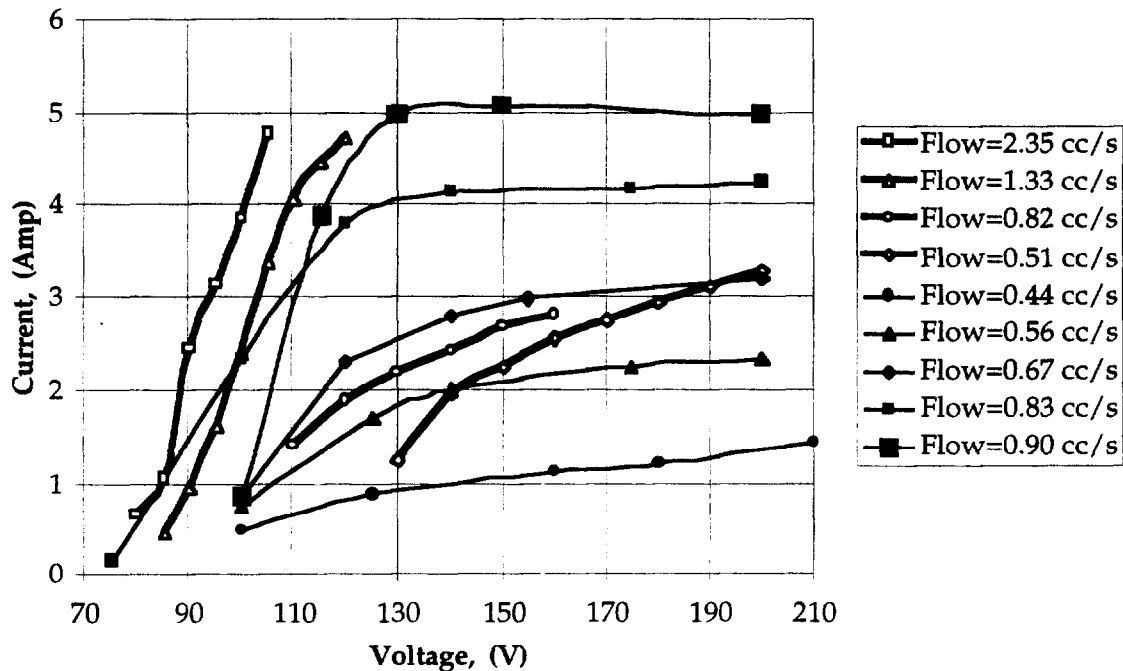


Figure 3. Comparison with [3]. (Thick lines - this work, scaled data; thin lines - data from [3])

disagreement at the lower flow rates: our curve for 0.82 cc/s appears too low by up to about 50%, and that for 0.51 cc/s appears too high by a similar factor, although both show the same trends as the data in [3] (saturating increase of current with voltage, with the rate of increase being reduced at the lower flows). Thus, overall, we observe current values consistent with those of [3], although with differences of detail. These may indicate errors in our flow rate calibration, or, for the lowest flow rate recorded, perhaps some current leakage.

Both our data and those in [3] illustrate clearly the rapid transition from a regime with poor ionization, at low flow rates, to one with good ionization at higher flows. More to the point, the parameter which controls ionization is seen to be the ratio of flow to diameter, as indicated by the scaling arguments. The implication for thruster miniaturization is that there is only a small margin of maneuver if we attempt to depart from strict scaling by allowing diameters which are somewhat larger than indicated by the inverse proportionality to power or flow rate.

For comparison to the work of [2], we note that their Type II thruster is of a design intermediate between SPT and TAL types, in that it has a short, but ceramic coated annular chamber, with a mean diameter of 48 mm. We scale currents and flows of our thruster by the ratio 48/3.7 for comparison. In [2], data for Argon operation are reported for flows of 1.5 Aeq (0.625 mg/s), 2 Aeq (0.833 mg/s) and 2.5 Aeq (1.04 mg/s). Using our lowest flow rate (0.13 mg/s) and the quoted scaling factor, we obtain a scaled flow of 1.69 mg/s (4.06 Aeq), higher than the highest of [2], although not by much. Thus, we limit our comparisons to this lowest flow, although, as noted above, there are indications that our current data may be too high for this flow.

The authors of [2] carried their investigation beyond Current-Voltage measurements, and obtained trust data, from which they were able to calculate overall thruster efficiencies (η), and some measure of their breakdown into three factors,

$$\eta = \eta_c \eta_u \eta_a$$

Of these, η_u is the propellant utilization fraction, i.e., beam ion flow rate divided by overall flow rate and η_a is the ratio of beam current I_b to anode current I_a , a high value indicating good utilization of the fraction of cathode electron current which is diverted to the annulus to initiate the ionization. The remaining factor, η_e , is the ratio of the effective ion acceleration voltage to the total applied voltage, and penalizes ionization at lower than anode potential. Fig 6b of [2] reports overall efficiency vs. specific impulse for the three flow rates indicated above; also shown there are contours of constant utilization factor η_u . The ratio η/η_u , namely the product ($\eta_a\eta_e$) can therefore be extracted, and it can be seen to be nearly constant for each flow rate, with values of 0.23 for 1.5 Aeq, 0.29 for 2 Aeq and .32 for 2.5 Aeq. A rough extrapolation to 4.06 Aeq then yields for our data a product

$$\eta_a \eta_e = .38$$

The separate value of η_e is only reported in [2] for the peak efficiency point of their data, as $\eta_e = 0.67$. We use this value throughout, which then implies $\eta_a = 0.567$. We then proceed as

follows to construct an estimated efficiency vs. specific impulse curve for our thruster:

- For each measured (and scaled) anode current I_a , the utilization factor is calculated as

$$\eta_u = \frac{I_b m_i \eta_a}{e \dot{m}}$$

from which $\eta = \eta_u \eta_a \eta_e$.

- Reading from our data the voltage V for the selected I_a , the effective jet speed is

$$c = \sqrt{\frac{2eV\eta_e}{m_i}}$$

and the specific impulse is then:

$$I_{sp} = \eta_u c/g$$

In Fig. 4 we show superimposed the data of [2] plus those obtained from the above procedure for our thruster. The implication of an efficiency as high as 22% at $I_{sp} = 1500$ sec is encouraging, although if our measured current is indeed too high, the whole curve will shrink in proportion towards the origin. It is interesting that our data

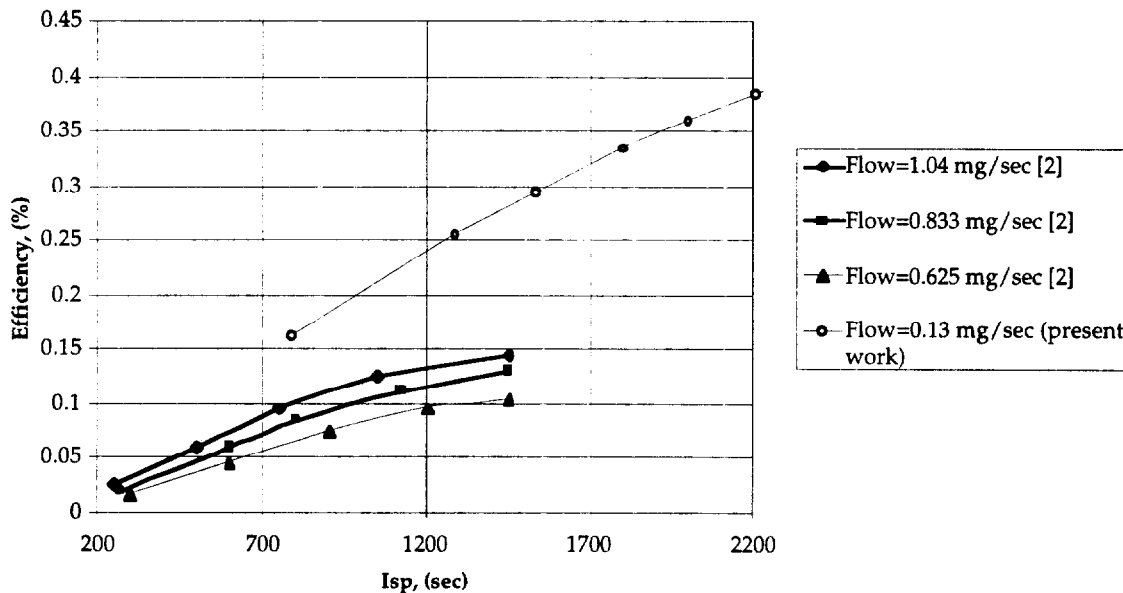


Figure 4. Comparison with [2].

do continue to higher I_{sp} values, which would then shrink into the range shown with still fairly

high efficiency. Because of its more difficult ionization, Argon is known to yield

substantially lower efficiencies than Xe in a given thruster (15% maximum vs 32 % in Xe, in the work of [2]). It appears therefore that our thruster has the potential for good efficiency, as one would expect if the scaling arguments hold, but confirmation must await thrust measurements, which are planned for the next few months.

4.0 Conclusions

A TAL-type of Hall thruster has been successfully designed and built, despite a number of difficulties encountered at the design stage and in the manufacturing process. It also appears from the comparison to larger Hall thrusters that it is possible to reproduce the same or similar efficiencies at small scale. Further testing is required to quantitatively evaluate the thruster performance. Procurement of a sensitive thrust balance in the future will allow us to make precise thrust measurements and to reach conclusions as to whether thruster's performance is adequate at such small scale. Thermal design, although marginal in this case, can be improved by using refractory materials for manufacturing of the anode as well as propellant capillaries. It is also important to ensure good thermal contact between the anode and the capillaries to conduct as much heat as possible out to the surroundings. This can be done by designing a monolithic anode which eliminates thermal mismatches, ensures good contact, and improves position tolerances between the anode and the magnets.

Although the use of permanent magnets for this design has proven to be successful, little further reduction in size of the thruster is possible as smaller devices would require yet larger confining fields. This is due to the limitations in the strength of the state-of-the-art magnetic alloys. If yet smaller devices are needed, some of the performance characteristics may need to be sacrificed to maintain adequate electron confinement.

Although the issue of reduced lifetime has not been given much attention, it deserves special consideration in any future work on micropropulsion. Drastic reduction in the lifetime, as predicted by the scaling laws, has not been experimentally verified and needs further

justification. No lifetime data are currently available on the large TAL thrusters. It is expected, however, that TALs will prove superior to SPT thrusters in terms of their lifetime, because the plasma region in TALs is pushed further out of the channel, thus possibly reducing erosion and improving lifetime in comparison to a similarly sized SPT. Hence, no conclusions can be made at this time as to whether or not the lifetime of a microthruster can be made adequate for a specific mission.

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