Characterization of Corona Ionization Based Microthrusters

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William P. Wright[1] and Philippe Ferrer[2]
University of the Witwatersrand, Johannesburg, Gauteng, 2000, South Africa

Abstract: A novel electrical micro-thruster (CorIon system) has been developed over the past five years at the University of the Witwatersrand, intended to be used commercially on small satellites and deep space probes. Experiments have shown that although the thruster operates, it is subject to instabilities in the plasma bridge due to high erosion rates which compromise continuous operation. Based on previous findings, a new design is being tested. The new design shares some of the major characteristics of the previous CorIon system while attempting to sidestep the plasma instability. Initial tests on a proof of concept system have shown that the new thruster is more stable and has a longer lifetime than the original CorIon system. The proof of concept system has a mass of 12 g and was able to operate at powers in the range of 1 W – 4 W at a mass flow rate of 0.675 mg/s using air as a propellant. Initial calculations suggest the electrostatic component of thrust to be approximately 50 µN. The measured thrust is expected to be greater due to other contributing processes such as ion-neutral momentum transfer interactions. The design features of this new system, the results of initial suitability tests on the proof of concept system and the results of electrical characterization, thrust measurements and plasma diagnostics performed to date will be presented. Measurement of two important quantities in these tests are the propellant mass flow rate and the thrust. Systems to perform these measurements have been developed in-house in both cases. The design, principle of operation and testing of these systems will be reported on.

Nomenclature

SEM	=	scanning electron microscope
ζ_T	=	total thruster beam divergence
η_T	=	total power efficiency
P_0	=	total power used
µ	=	mass of a propellant atom
q	=	charge of a propellant ion
I	=	current
$\dot{m}$	=	mass flow rate
C	=	orifice flow co-efficient
A_2	=	area of the orifice
ρ	=	propellant density
P_1	=	pressure in cavity 1
P_2	=	pressure in cavity 2

I. Introduction

[1] PhD Student, School of Physics, 314727@students.wits.ac.za
[2] Senior Lecturer, School of Physics, philippe.ferrer@wits.ac.za

MICROSPACECRAFT are rapidly becoming competitive instruments in both military[1] and civilian[2] space programs. The development of such microspacecraft necessitates the miniaturization of complex subsystems such as scientific instruments[3] and power conditioning systems[4]. Spacecraft propulsion systems are no exception to this especially considering that, not only are micropropulsion systems developed as the primary propulsion systems of microspacecraft, they can also be used as the attitude control systems of larger spacecraft that are required to be extremely stable[5].

However, the process of miniaturization of existing propulsion technology has been marred by scaling problems[6]. These issues can be overcome using complicated design features such as the addition of magnetic fields[7]. Another option is explore novel propulsion concepts that are already small in size and develop them to meet mission requirements. A summary of the current state of both novel micropropulsion concepts and miniaturized versions of existing propulsion systems can be found elsewhere[8].

While many of these technologies are being intensely developed and are showing promise[9], they are not yet at a stage of development where they can meet the strict size and mass requirements of microspacecraft[10]. This leaves room for promising new technologies to be explored in the hopes of filling a gap in the market. Two such technologies are being studied at the Space Propulsion Research Laboratory based at the School of Physics in the University of the Witwatersrand: the CorIon system and its successor.

II. The CorIon System

CorIon is a portmanteau of the words corona and ionization and was the name given to the first electrostatic micropropulsion system developed at the Space Propulsion Research Laboratory based at the University of the Witwatersrand. This name was chosen as the corona mechanism is the primary ionization mechanism exploited by the system. The thruster is described in detail elsewhere[11,12], but a brief discussion of its principle of operation as well as its shortcomings will be presented to add context to its successor.

A. Principle of Operation

The system utilizes an ionization/acceleration coupling mechanism to generate thrust and to achieve minimization. Two metal needles imbedded in an insulating material form the bipolar design of the thruster. This is shown in the schematic diagram Fig. 1. A high voltage power supply is connected the needles to set up a potential difference and a gas flow system is connected to supply propellant.

The stressed shape of the needle electrodes means that when a high potential is dropped across the electrodes, positive and negative corona ionization are induced by the resulting high electric fields around the corresponding needle tips. Thrust is then generated by utilizing the same electric field to accelerate the resulting ions and electrons away from the thruster.

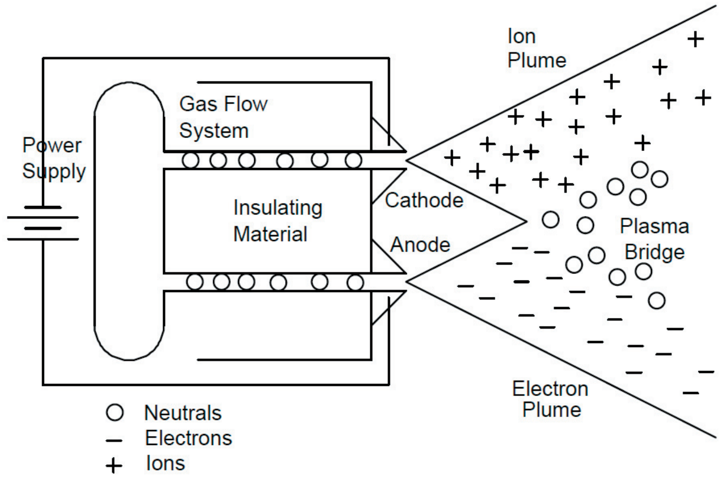

Figure 1. A Schematic Diagram of the CorIon System

B. Advantages

Experiments on the system have revealed a number of favourable qualities that make the thruster attractive as a micropropulsion system. Firstly, the corona ionization mechanism has a low energy cost to produce an electron ion pair[13] meaning it is a very efficient process by nature and could be used to produce a very efficient thruster design. With the correct operating parameters implemented, the bipolar design means that a plasma bridge should form between the positively and negatively charged plumes creating a quasi-neutral plasma and the system should be able to operate without the need for an external neutralizer. The design is simple and easy to construct and these features suggest reliability and easy repair should the need arise. The small size of the system means that it can be made very light and this introduces the possibility of stacked operation where a number of thrusters are used together to create a larger overall thrust. Finally the system is incredibly versatile as any gaseous propellant can be used with the thruster. Table 1 shows a very simple comparison between the CorIon system and other competing systems. The CorIon thruster competes well and shows promise as a propulsion technology.

System	Thrust (in µN)	Mass (in g)	Power Used (in W)	Reference
CorIon	50 (expected)	5 (thruster)	1.5	11
Vacuum Arc	10-200	50 (thruster)	1-20	14, 15
Laser Ablation	680	750 (thruster)	9	16
FEEP	0.1-150	1400 (system)	6	17
PPT	850	350 (thruster)	5-33	18, 19
Gridded Ion	200-500	210 (thruster)	30	20

Table 1. Comparison between the CorIon system and competing technologies.

C. Disadvantages

In spite of the promise shown in Table 1., there are a number of issues that hamper the development of the CorIon system into a fully functional micropropulsion system. The biggest issue is concerned with the high erosion rate of the needle tips which form the electrodes of the thruster. Due to their small size, a high power density is present at the needle tips, which, while desirable, results in high energy ions impacting on the needle tips and the needles are sputtered away resulting in a short thruster lifetime. This is because the sputtering of material from the needles affects the needle shape which has an impact on the gas flow characteristics of the system as well as the electric field set up when a potential is dropped across them. This in turn affects the plasma characteristics of the system, most notably the plasma bridge which is required for continuous operation.

This fault has even resulted in the needles being blocked with sputtered material which prevents system operation. This behaviour has limited the stable operating lifetime of the system to a period of approximately 15 minutes. This feature of the system has necessitated a redesign which will be elaborated on further below.

III. The Redesigned System

Inspiration for this system redesign was drawn from a conventional glow discharge tube, largely due to the fact that this system is very well understood and has been under study for over 100 years[21]. Also, a number of different discharge regimes exist, including, but not limited to a stable glow discharge, an arc discharge and a pulsed mode of operation that has been utilized in electronics applications when the DC signal used to initiate and sustain the discharge is replaced with an AC signal[22]. Should this mechanism be adapted into a propulsion system, the varying discharge regimes offer a variety of modes of operation that could be exploited to generate thrust, increasing system versatility.

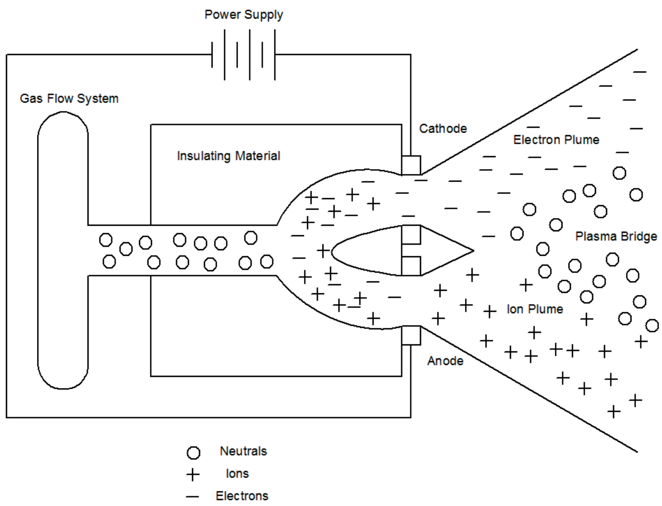

Figure 2. A Schematic Diagram of the Redesigned System

A. Principle of Operation

Just as in a glow discharge tube, a plasma would be generated in a low pressure gas via a Townsend discharge. The discharge would be confined by a tube made of an insulating material and would be initiated by two oppositely charged electrodes placed at either end of the confining tube. In its simplest incarnation, the thruster would consist of such a discharge tube bent into a 'U' shape with open ends and ring shaped electrodes replacing the conventional electrodes placed at the tube ends. The opening in the insulating tube and the ring electrodes will allow for the generated plasma to exit the thruster. With the addition of a gas flow inlet to replenish exhausted propellants the design is easily converted into an electrostatic thruster.

It is hypothesized that when a potential difference is dropped across the electrodes, a similar glow discharge that is created in a discharge tube can be established and the opening at the ends of the tube mean that the resulting ions and electrons can be accelerated away from the thruster by the corresponding electrodes. This simple geometry can be experimented with to exploit Paschen's Law[23] and optimize the system, generating greater thrusts at lower mass flow rates and with greater electrical efficiency. A schematic diagram depicting the redesigned system is shown in Fig. 2.

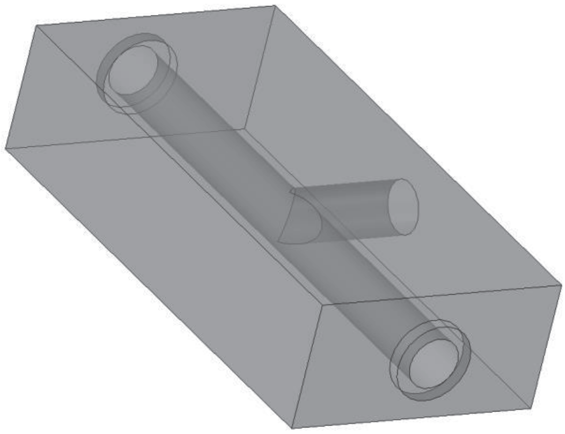

Figure 3. A Schematic Diagram of the Redesigned System

B. Proof of Concept

The proof of concept system as shown schematically in Fig. 3 consists of a conventional discharge tube drilled into a piece of Acrylic plastic with the ends left open and a gas inlet drilled at right angles to the discharge tube. Ring electrodes made of 308 grade steel are positioned at the open ends of the discharge tube. The materials were chosen to facilitate rapid changes in design with short turn around times. The purpose of the system is to test if a discharge can be sustained inside the discharge tube while ions and electrons are being ejected from the thruster. Lifetime and stability tests were performed to determine the potential of the system as a thruster in comparison to the CorIon system and an attempt at basic electrical characterization consisting of a set of IV characteristics measurements was conducted.

1. Results

The system was run in a vacuum chamber with a diameter of 760 mm and a height of 200 mm at pressures between 10^{-4} torr and 10^{-5} torr. A digital high voltage power supply was used to supply the potential drop at powers in the range of 0 W to 4 W and an in-house developed gas flow system was used to supply the propellant which, for these tests, was air at mass flow rates of between 0.6 mg/s and 0.7 mg/s.

Experimenting with operating parameters showed 3 distinct modes of operation: A discharge tube mode, where the plasma is confined inside the thruster and no plasma is ejected from the system (occurring at powers > 1 W); A pulsed mode where sporadic ejection of ions and electrons is observed from the ends of the thruster (occurring at powers between 1 W and 1.5 W) and a continuous mode of operation where electrons and ions are observed to be ejected from the corresponding opening in the thruster without interruption (occurring at powers < 1.5 W). This mode of operation is depicted in Fig. 4.

Lifetime and stability tests showed that the proof of concept system was able to log in excess of 5 hours continuous operating time with little to no variation in operating parameters. This is a great improvement on the original lifetime of the CorIon system, especially considering the materials used were not designed to be subjected to these conditions. Considering the electrodes were the primary point of failure of the CorIon design, the electrodes of the redesigned system were studied using scanning electron microscopy (SEM) to determine the extent of the damaged suffered by the electrodes. A SEM image depicting the inner rim of the electrode subjected to ion bombardment is depicted in Fig. 5. This image shows that the damage to electrodes is minor and none of the extensive damage and clogging observed in the CorIon is present.

The IV characteristics of the system were taken at 2 different flow rates, 0.611 mg/s and 0.675 mg/s and are depicted in Fig 6. From these IV characteristics, a set of resistance versus current measurements and power versus current measurements were obtained. A full theoretical analysis has yet to be attempted and many more experiments need to be conducted, but it is encouraging to see that the IV characteristics obtained bare similarities to the IV characteristics of a conventional glow discharge tube[24]. This means we can delve into the wealth of knowledge around discharge tubes in an attempt to explain the underlying physics. The resistance versus current measurements shown in Fig. 7 show an exponential decrease in resistance with increasing current. This shows how the non-conducting propellant becomes conducting as it is ionized. The power versus current measurements shown in Fig. 8 depict a linear increase in power used with current. A slight bump is present in the region where the system transitions from the pulsed mode of operation to the full continuous mode of operation. The power versus current curve taken at a higher mass flow rate shows a less steep gradient than the curve taken at a lower mass flow rate. This makes sense as a higher mass flow rate will result in a higher gas pressure and a higher density of propellant atoms, shortening the mean free path of ionizing electrons and allowing the discharge to be sustained at a lower power[25].

Figure 4. The Proof of Concept System in the Continuous Mode of Operation

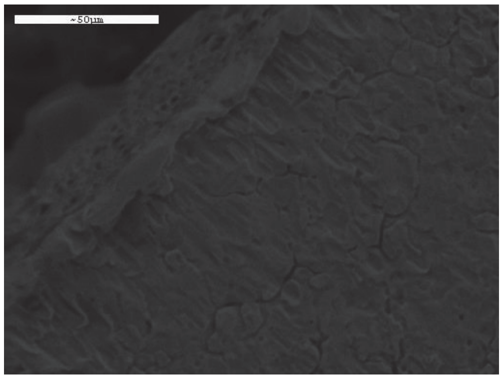

Figure 5. SEM Image of the Inner Rim of the Ring Electrode.

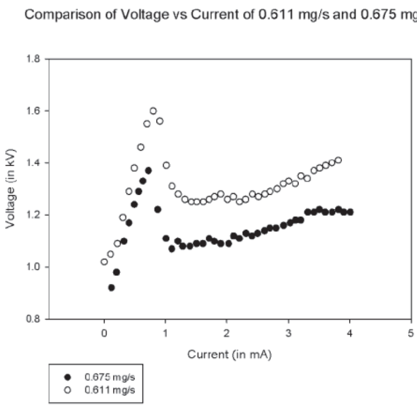

Figure 6. IV Characteristics of the Proof of Concept System

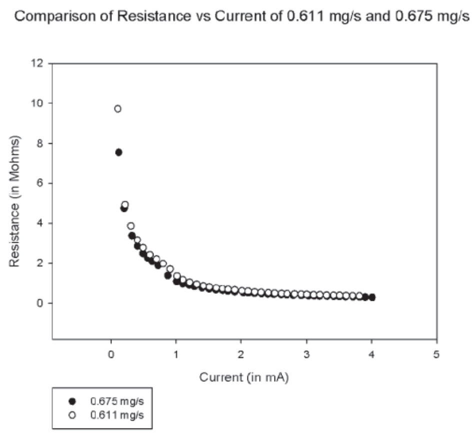

Figure 7. R vs I Measurements of the Proof of Concept System

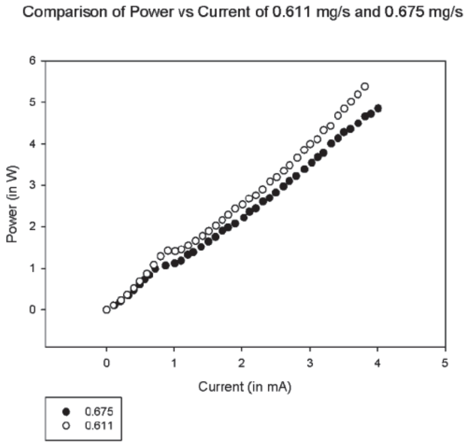

Figure 8. P vs I Measurements of the Proof of Concept System

Figure 9. The 'U'-Shaped System in the Continuous Mode of Operation.

C. 'U'-Shaped Design

The simple 'U'-shaped geometry discussed previously is currently being explored and initial tests have shown promising results. The same modes of operation observed in the proof of concept system have been seen in the 'U'-shaped system and Fig. 9 shows the system under continuous operation. No data has been collected at this stage as novel construction techniques such as 3D printing using bio-plastics are being explored to ease prototyping.

IV. Measurement Equipment

In order to study the thrust performance of an electric propulsion system, a number of specialized pieces of equipment are required. A thrust measurement balance is required to measure the thrust produced by the system and a mass flow measurement system is required so that the mass flow rate can be measured and adjusted. While a number of other systems exist to measure thrust[26,27], and commercial mass flow measurement systems can be purchased, systems to perform these tasks have been developed in-house to cater for our specialized requirements.

A. Thrust Measurement System

At time of writing, the laboratory is working on developing a new thrust measurement balance that utilizes a novel magnetic coupling mechanism to measure thrust. The details of this balance will be published elsewhere and once completed; accurate thrust measurements of both the CorIon system as well as the new redesigned system will be performed.

However the electrostatic component of the thrust can be approximated by using a generalized form of the Rocket equation for electrostatic propulsion systems[28] given in Eqn. 1 below:

$$T = \zeta_T \sqrt{2\eta_T P_0 \frac{\mu}{q} I} \tag{1}$$

Where ζ_T is the total thruster beam divergence, η_T is the total power efficiency of the thruster, P_0 is the total power used, μ is the mass of a propellant atom, q is the charge of a propellant ion and I is the current used. By assuming singly ionized nitrogen as the propellant, a power of approximately 4 W, a current of approximately 4 mA, a thruster beam divergence of 0.8 (corresponding to a divergence angle of 54 degrees) and a total power efficiency of 0.77 (with losses associated with general discharge losses and losses to the electrodes), the electrostatic component to the thrust will be approximately 50 μN. The total thrust generated is expected to be larger due to the influence of ion-neutral momentum transfer interactions

B. Mass Flow Measurement System

In order to measure the mass flow rate of propellant through the thruster, a system based on an orifice flow meter[29] has been developed. The orifice flow meter consists of two cavities separated by a membrane with an orifice in the membrane which is much smaller than the surface area of the membrane. If the pressure difference between the two cavities is known, the mass flow rate of material through the orifice can be determined. This relationship is given by Eqn. 2.

$$\dot{m} = CA_2\sqrt{2\rho(P_1 - P_2)} \tag{2}$$

Where $\dot{m}$ is the mass flow rate, C is the orifice flow co-efficient, A_2 is the area of the orifice, ρ is the density of the material flowing through the orifice and P_1 and P_2 are the pressures in either cavity. A calibration curve depicting the relationship of the mass flow rate and the pressure difference between the cavities is shown in Fig. 9 with Eqn. 2 fitted to the data.

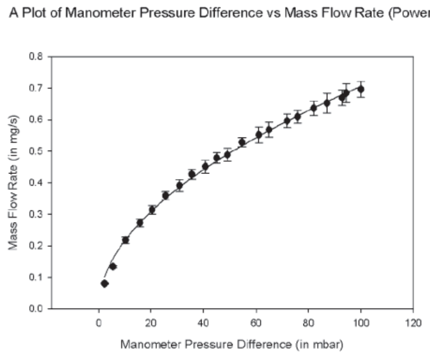

Figure 9. Calibration Curve for the Orifice Mass Flow Measurement System

V. Conclusion

A novel type of electrostatic micropropulsion system that utilizes the corona mechanism as well as ionization/acceleration coupling to achieve miniaturization and thrust is being studied at the University of the Witwatersrand. Unfortunately the system has been shown to suffer from some instabilities that hamper continued operation. An alternative system that draws inspiration from a conventional discharge tube has been developed that shows promise as a replacement system exhibiting greater stability and a longer lifetime than the original CorIon system. The system needs to be studied in greater detail using more comprehensive electrical characterization, thrust measurements plasma diagnostics and the system needs to be modeled so that the system can be optimized and developed into a functional propulsion system.

Acknowledgments

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