The Hollow Cathode as a Micro-Ion Thruster*†

Paolo Gessini, Stephen B. Gabriel
Astronautics Research Group
School of Engineering Sciences
University of Southampton
Highfield, Southampton
Hants, SO17 1BJ
United Kingdom
+44-2380-594896, +44-2380-593222
pg4@soton.ac.uk, sbg2@soton.ac.uk

David G. Fearn
Space Department, Y72 Building
QinetiQ
Farnborough
Hants, GU14 0LX
United Kingdom
+44-1252-392963
dgfearn@scs.dera.gov.uk

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Hollow cathodes (HCs) can, in certain regimes, ionize a high fraction of propellant. Ions of sufficient energy to cause significant sputtering have been detected. In this paper, through a critical review of experimental results and theoretical models, we estimate the ion flux and hence the thrust that can be obtained. A target thrust balance has been designed. The target is part of a cantilever beam. By measuring the displacement of the free end of the beam the thrust can be calculated. The target is also used as a Faraday plate to measure the ion current. From the total momentum flux (thrust) and mass flow rate the specific impulse can be determined. By appropriately biasing the target, the ion average velocity can be assessed from the ion thrust and mass flow rate (current). Characterizing the ion emission and the thrust obtainable from a HC is the first step toward creating a micro-ion thruster that could provide onboard propulsion for a variety of small spacecraft missions.

Introduction

In recent years, the trend towards increasingly smaller spacecraft has generated the need for micro-thrusters. Also on larger spacecraft it is necessary to provide low-thrust auxiliary propulsion over many years, if possible consuming less propellant than needed by conventional chemical thrusters. By using small electric thrusters, with a high specific impulse (SI), significant propellant-mass savings can be achieved, which in turn translate into a reduced launch cost, an extended spacecraft lifetime or extra payload. In any case, there is a significant financial benefit from employing high SI propulsion technology.

Not all types of thruster, however, can be scaled down easily. In gridded ion engines and Hall-effect thrusters (HETs), magnetic fields are used to contain the electrons in the discharge volume, increasing their path length to a few ionization mean free paths. This provides a high probability of ionization before they are lost by contact with the interior surfaces.

Where magnetic fields are used, scaling down involves stronger and stronger fields, to ensure that the electrons are adequately contained within the available volume. This is because the electrons spiral around and progress along the magnetic field lines with a

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radius of gyration (Larmor radius) inversely proportional to the magnitude of the field. Therefore, scaling down a 10 cm beam diameter ion thruster to a millimeter diameter would require increasing the magnetic field strength from 0.1 to 10 Tesla, in order to maintain efficient electron containment[1,2]. Magnet weight and power requirements could easily become prohibitive.

In addition, efficiency falls dramatically with size, partly due to decreasing volume-to-area ratio. This is because ionisation is a volume phenomenon, whereas losses are proportional to area, so as the volume-to-area ratio falls as thrusters become smaller, so does the efficiency, which is proportional to it. In particular, for the cylindrical geometry generally adopted in ion thrusters, decreasing both radius and length by a certain factor will decrease the volume-to-area ratio by the same factor.

Thus the prospects of designing successfully a very small ion thruster of traditional design to operate at acceptable efficiency are not good. For this reason, there has recently been some interest in the possibility of developing non-magnetic micro-ion thrusters[1,3].

However, it has been found by several research groups that hollow cathodes (HCs) can produce significant amounts of relatively high energy ions, with energies often well above keeper or discharge plasma potential[4-9,10]. This suggests that a HC, by itself, might be capable of producing an appreciable thrust at a relatively high value of SI.

This observation might not be particularly significant if the degree of ionisation within the plasma plume emerging from a HC were very low, as has often been assumed in the past, as any thrust would then be very small, and might not be of practical interest. However, recent studies by Crofton[4,5,11] suggest that this earlier assumption may not be correct. From the high level of Xe^{2+} observed in the plume emitted by the cathode of a T5 thruster, he concludes that the plasma emanating from a HC is almost completely ionised near the orifice, at least for certain flow rate and orifice current density conditions[4,5].

If HCs can be used as thrusters, as suggested in this paper, it should be noted that they are a well-established, flight-qualified technology. They have a very long proven life, with up to 2.8×10^4 hours having been demonstrated at the NASA Lewis Research Center (LeRC) with xenon[12]. This life test was terminated due to an ignition failure, when the cathode tip temperature exceeded 1600 K. Estimates of lifetime for the UK-25 HC yield more than 10^4 hours with a tip temperature of the order of 1400 K[13,14]. This is entirely consistent with many missions of interest.

It is concluded that HCs could be developed into simple and effective micro-ion thrusters. In order to do this, we need first of all to measure accurately their ion emission characteristics and to determine possible ways in which they might be enhanced. This will allow us to assess the thrust and SI that can be obtained and to establish the range of appropriate missions for these devices.

Review

HCs have been built and operated for many years, mainly in support of their role as efficient, long life electron emitters in gridded ion engines and HETs. Many efforts aiming at a better understanding of their physics have been ongoing in several countries, with the ultimate objectives of reducing power input for a given electron emission current and increasing lifetime. Numerous papers about HC behaviour, including both experimental results and theoretical analyses, have been published since the 1970s[15,16,17,18].

The discharge to a HC is initiated, in most cases, by heating it to a temperature of about 1300 K, passing a flow of propellant gas through it, then applying a potential to a keeper electrode situated adjacent to the tip. It is usual to continue to draw a current to this electrode under steady-state operating conditions, although this is not always the case with HET applications. This is to ensure that the discharge and cathode emission process will continue even if the main current to the anode or to the ion beam is interrupted. Hence the name “keeper” electrode, or simply keeper[19], is used. Early on it was discovered[20], and later confirmed[21,19], that an enclosed-keeper configuration can significantly aid discharge stability and reduce the amplitude of electrical noise. This type of configuration will be adopted in our experimental work, and is described in another section of this paper. A HC/keeper assembly is shown schematically in Figure 1 (courtesy of QinetiQ).

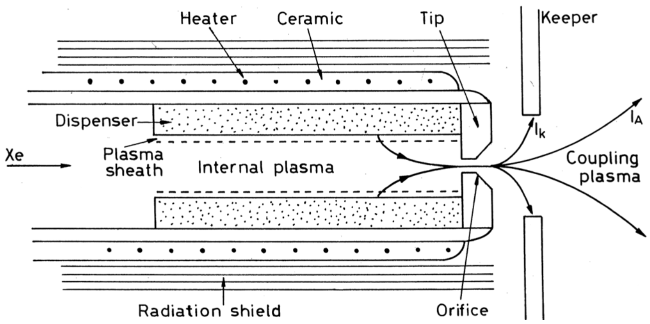

Figure 1 – HC/keeper assembly (QinetiQ).

Although many possible electron-emission mechanisms have been invoked to explain the high current densities, often of the order of 50 A/cm^2, obtained from the surface of the dispenser located within the cathode, the field-enhanced thermionic process would seem to dominate under many circumstances[18,22]. This occurs because a dense internal plasma is generated within the HC, as confirmed by both probe[18] and spectroscopic[23] measurements. A very thin sheath then forms to separate this plasma from the wall, and the potential drop across this plasma sheath provides the high electric field at the surface needed to enhance the normal thermionic emission to the high current densities observed. The Richardson-Dushman equation

$$j_{th} = AT^2 e^{-\frac{e\varphi}{kT}}$$

where $A \cong 60\ Acm^{-2}K^{-2}$ is the Richardson constant, T the temperature of the emitting surface and φ its work function is therefore modified to include the Schottky effect. This is done by introducing an effective work function

$$\varphi_e = \varphi - \sqrt{\frac{eE}{4\pi\varepsilon_0}}$$

and rewriting the equation for field-enhanced thermionic emission as

$$j_S = AT^2 e^{-\frac{e\varphi_e}{kT}} = j_{th} e^{4.389\frac{\sqrt{E}}{T}}$$

where E is the electric field at the emitting surface in V/cm[24]. From the above equation it is clear how the emitted current density is greatly increased by the presence of an electric field at the emitting surface.

Various experimental results[4-9,10] have shown that relatively high directed ion energies can be generated in the plasma emerging from the orifice of a HC, and several authors have suggested[4,25,26] that it should be possible to obtain significant ion fluxes from HCs, especially if the efficiency of ion extraction is improved. In parallel, modelling efforts by different authors have analysed the intricacies of the different physical mechanisms operating in the insert and orifice regions of a HC. As generally pointed out, however[4,27], the behaviour of HCs is complex and remains poorly understood, with no widely accepted theory explaining their high performance.

Experimental Results

Since the end of the 1980s[28] some investigators have observed that, under certain conditions, significant high-energy ion emissions may occur from a HC. Reasonably high fluxes of ions have been measured, even at energies greater than any applied voltage[4-9,10]. Such energies are sufficient to induce substantial sputter erosion rates, especially of the baffle disc in the Kaufman-type gridded ion thruster[6,9,28]. This was actually the main initial concern fostering this kind of investigation. These experiments were undertaken under widely different conditions, in particular with respect to measurement techniques employed and discharge configurations adopted, so a direct comparison of the results obtained is not necessarily valid.

HC-Keeper-Anode Configuration

Experiments carried out at Colorado State University have consistently employed a cylindrical-anode configuration. This was chosen in order to simulate typical HC operation within the main discharge chambers used in gridded ion propulsion systems. The keeper was a toroidal ring constructed from tantalum wire, positioned 1.0 mm downstream of the HC orifice in an open configuration. As regards instrumentation, Friedly and Wilbur[9] used a retarding potential analyzer (RPA) for their experiments, whereas Kameyama and Wilbur[7,8], employed an electrostatic energy analyzer (ESA).

Williams *et al.* at the University of Michigan[29] also employed a cylindrical anode, but performed their measurements with laser induced fluorescence (LIF) techniques and a Langmuir probe. A keeper plate was located 4.0 mm downstream of the HC orifice. This open-keeper configuration permitted very fine spatial resolution to be achieved using LIF in the cathode-to-keeper gap. Patterson and Fearn (DERA) adopted an anode-plate (with a central hole for optical access) and open-keeper configuration. The keeper was a circular plate with a central orifice of 5 mm diameter. The HC position could be varied at will with respect to the keeper by means of an externally actuated micromanipulator. Measurements were performed with an RPA[10]. Latham, Pearce and Bond at the Culham Laboratory[6] employed an RPA in a UK-25 ion thruster configuration.

HC-Keeper Configuration
Experiments at Culham and at the University of Michigan by the same authors as mentioned above[6,29] were also made for the simple case of a keeper discharge only. Crofton (The Aerospace Corporation) took measurements with an RPA and a quadrupole mass spectrometer (QMS) using a keeper electrode with 3.0-mm-diameter aperture just downstream of the HC in an enclosed configuration[4,5,11]. The data acquired from this work were the first to indicate that the degree of ionisation in the plasma plume emitted by a HC might be very much higher than assumed previously.

These experiments are the most relevant to the discussion presented in our paper, because they were performed in a configuration similar to the one we intend to adopt, namely a HC/keeper discharge. This might impose severe limitations on the current we will be able to draw from the cathode to the keeper anode, unless we increase the dimensions of the keeper. In order to do so, we could either change our design (currently an enclosed keeper) or “extend” the keeper by connecting another anode to the same power supply, thus keeping it at the same potential.

The HCs used in the experiments at the University of Michigan were provided by the NASA Glenn Research Center (GRC). High-energy xenon ions were detected, which were consistent with the potential-hill model of high-energy ion production[9]. Under an agreement with GRC the dimensions of the cathode orifices were not published[29]. This makes it difficult to compare their results with those obtained using different devices.

Crofton used a xenon HC originally designed for use as the main cathode in the UK-10 ion engine. An engineering model of this thruster, designated T5, has been well characterized by the same author[30]. Measurements with the RPA and the QMS were taken at different angular positions with respect to the cathode axis ($\phi = 0°$) and at different operating points. An interesting observation that can be made, especially relevant to the evaluation of the obtainable thrust, concerns the divergence of the ion beam. The angular dependence of the ion current at two operating points (OPs) is shown in Figure 2[4]. OP 5, at a lower mass flow rate (MFR) (0.04 mg/s) corresponds to a higher peak and a lower full-width-half-maximum (FWHM) than those measured at OP 1, with a MFR of 0.1 mg/s.

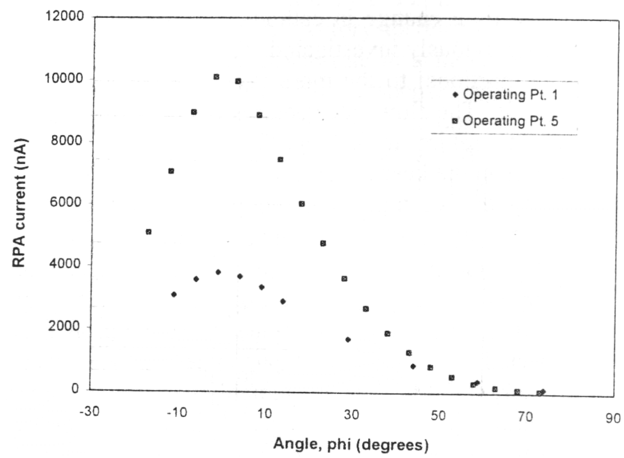

Figure 2 – Angular distribution of ion efflux (Aerospace Corp. data)[4].

Visual observation indicated a more extended plume, about 3 cm long, at OP 5. Penetration and divergence of the jet are therefore pressure dependent. It would be interesting to perform similar experiments in a facility with a pumping system capable of handling different propellant MFRs while keeping the background pressure sensibly constant. In Crofton's experiments, an increase in MFR from 0.04 mg/s (OP 5) to 0.1 mg/s (OP 1) caused an increase in test chamber pressure from 6.8×10^{-6} Torr to 1.4×10^{-5} Torr. The influence of the background pressure might therefore conceal any possible effect of the varying MFR on the plume structure, as well as any effect of the keeper potential and current (33.8 V, 1.30 A and 26 V, 1.12 A respectively at OPs 5 and 1).

RPA measurements show relatively large amounts of ions with energies higher than the keeper voltage. Such ions are more energetic at small ϕ[4]. QMS measurements indicate the presence of a high level of plume Xe^{2+}. This suggests that the fractional ionization of xenon near the cathode orifice may approach unity, at least at the higher keeper current operating points[4,5]. Xe^{2+} may also play an important role in the formation of high-energy Xe^{+}. A doubly-charged ion would have √2 higher velocity than a singly-charged one, neglecting collisional effects. Collisions between these species can result in momentum transfer, with Xe^{+} being the partner that gains energy. To a good approximation, charge exchange will interchange the energy distribution of the collision partners. The conversion of multiply-charged ions to Xe^{+} in the plume through charge exchange with neutrals and other ions, therefore, produces high-energy singly-ionized xenon[5,11].

As an example of these processes, King and Gallimore[31,32,33,34] and Gulczinski and Gallimore[35] suggest that these two mechanisms, momentum-exchange and charge-exchange collisions, may be acting in the plume of HETs (SPT-100 and P5, respectively). Even at modest density levels and Xe^{2+} : Xe^{+} ratios (~12% in the SPT-100[31]) a high energy "tail" in the ion energy distribution function is produced, due to ions having energies greater than the potential applied to the thruster discharge.

Even if the T5 HC approaches full ionization at the higher levels of orifice current density[4,5], the propellant mass utilization does not, in general, exceed 10%[4]. This latter parameter is defined as the ratio of extracted ion current over the equivalent current of 100% singly-ionized xenon. Such a discrepancy is probably caused by the fact that most ions are neutralized before they can escape through the keeper orifice[4]. Inside the cathode, and even more so in the expanding plume, the electron temperature T_e is much lower than the first ionization potential for xenon (12.13 eV). Recombination is thus bound to be significant[36]. Semenov and Batuev[25] were able to improve sensibly the propellant mass utilization in an argon flow by using an accelerating electrode. Their device, however, was very different from the HCs intended for space propulsion, especially in presenting a very wide aperture through which the ions could be extracted.

The experiments conducted by Latham, Pearce and Bond at the Culham Laboratory[6] are particularly relevant here, because they employed during most of their work a cathode essentially identical to the T6 HC, on which our cathode is based closely. The main difference was that their HC had an orifice diameter of 0.6 mm chamfered to 0.8 mm. This relatively small orifice size limited discharge currents to 10 A, to avoid erosion. Orifice erosion and the need to reduce operating temperature was the reason that prompted the further increase of the T6 HC orifice diameter, originally 0.75 mm countersunk at an angle of 45° to a depth of 1 mm, up to 1.3 mm, previous experience[22] having suggested that this would be effective. The reduction in tip temperature achieved in this way was about 80 K[37]. The thruster experiments at Culham went up to 40 A discharge currents[38]. They used several different cathodes, including ones that they manufactured themselves to their own designs. The RAE/DERA HC, which was the cathode used during most of the work, had a 0.75-mm-diameter orifice, not chamfered, and its tip was 1 mm thick.

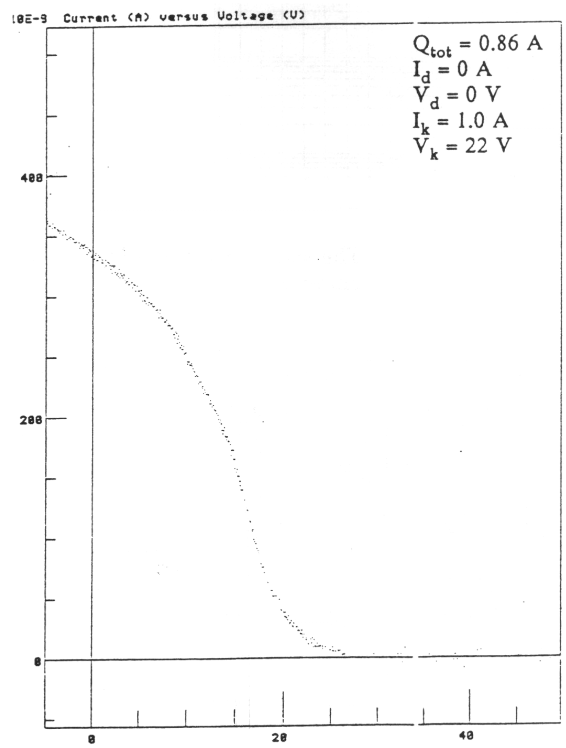

Figure 3 – RPA trace at 0.86 A eq. Current (Culham data)[6].

The measurements at Culham were made by fitting a compact RPA into a 6-mm-diameter hole drilled in the centre of the tantalum baffle, 55 mm downstream of the HC. Figures 3 and 4[6] show a typical RPA trace and the corresponding ion energy spectrum for a cathode flow of 0.86 A equivalent current of xenon. This was obtained by differentiation of the curve in

Figure 3. The equivalent current is defined as

$$J_{eq} = \frac{m}{m_{Xe}} e$$

where m is the mass flow rate, m_{Xe} the atomic mass of xenon and e the electron charge. Keeper voltage and current are, respectively, 22 V and 1.0 A.

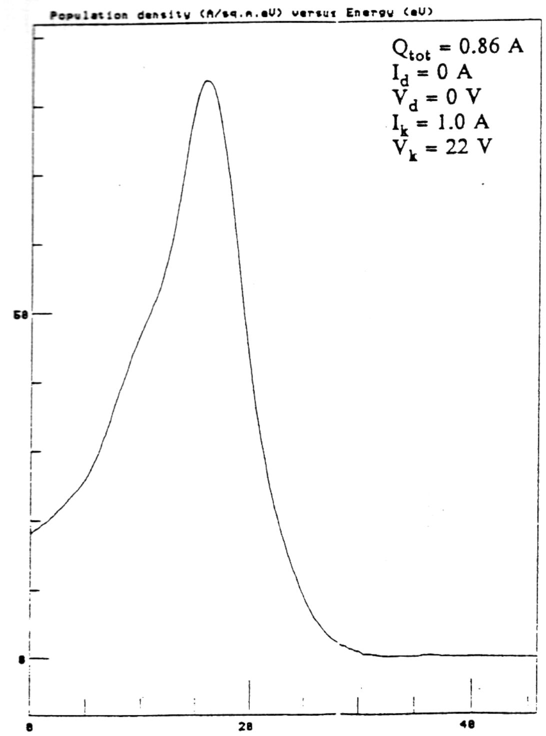

Figure 4 – Ion energy spectrum from Figure 3 (Culham data)[6].

The ion energy peak is below keeper potential, but there are ions at least up to this potential. On lowering the cathode mass flow rate at fixed keeper current, the "tails" of ions with energies in excess of keeper potential become increasingly significant, even if the peaks of their energy distribution functions remain below keeper potential. This is shown in Figure 5[6], for a keeper current again of 1.0 A, a keeper voltage of 42 V and a flow rate of 0.07 A equivalent current.

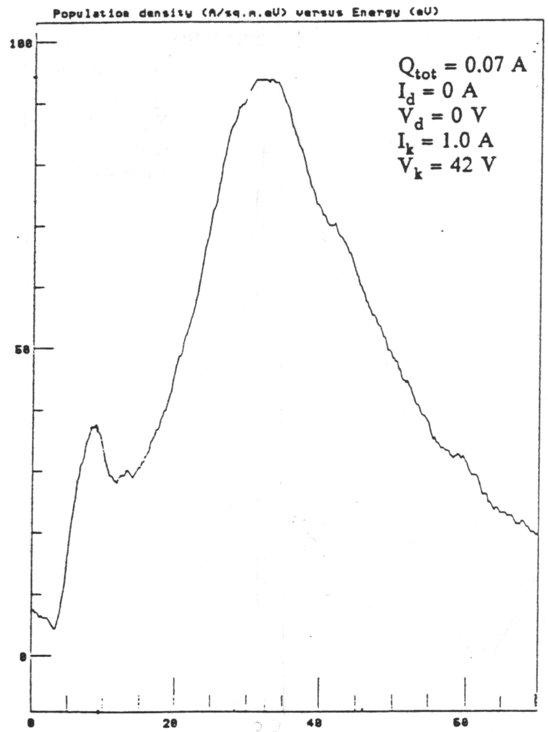

Figure 5 – Ion energy spectrum at 0.07 A eq. current and 1.0 keeper current (Culham data)[6].

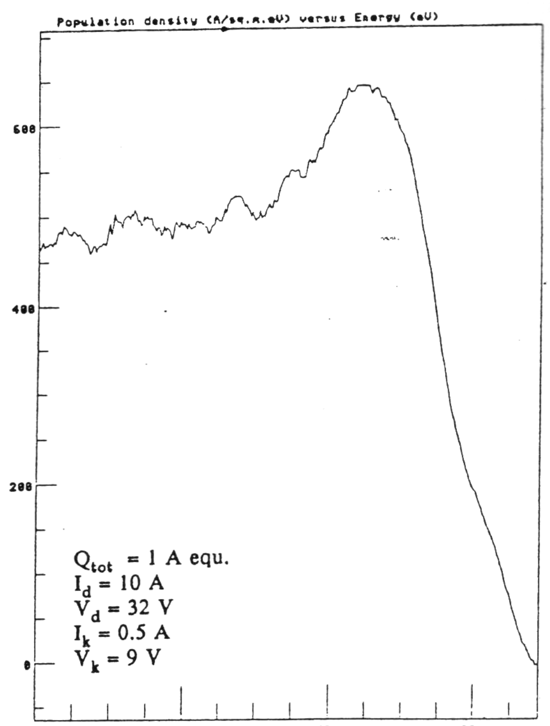

Figure 6 – Ion energy spectrum at 1 A eq. current and 10 A discharge current (Culham data)[6].

It is also interesting to examine the behavior when the discharge supply was operated, because the total current is what is relevant to the phenomena inside the HC and, as we said above, currents higher than those reported here will be possible in a T6-keeper discharge, especially using an "extended" keeper electrode. The total propellant flow was split in the ratio 70:30 between main and HC propellant feeds.

As the discharge current was increased and the flow rate lowered, the increase in the high-energy component, well above discharge voltage, was dramatic. This is shown in the ion energy spectrum in Figure 6[6], for a discharge current of 10 A, a discharge voltage of 32 V and a flow rate of 1 A equivalent current.

Two possible mechanisms were suggested by the investigators for the production of the high-energy ions observed[6]. Together with the interaction between multiply and singly ionized species described above, they remain, up to the present, the most valid, even if only qualitative, ideas suggested.

The potential-hill model, proposed by Friedly and Wilbur[9], postulates the creation, in the plasma near the HC orifice, of a region at a positive potential in excess of keeper potential. This would arise due to positive space-charge build-up resulting from substantial ion production via collisional ionization by high-energy electrons.

The orifice-pinch model, proposed by Latham, *et al.*[6], postulates a magnetohydrodynamic (MHD) effect associated with current densities, in the orifice region, high enough to produce a pinching effect. The plasma would then be accelerated according to the equation:

$$\rho \frac{Dv}{Dt} = j \times B - \nabla p$$

where ρ is the plasma mass density, v the flow velocity, j the current density, B the magnetic induction and p the plasma pressure.

Theoretical Models

Various models of HC operation have been proposed in the last twenty years, ranging in complexity from simple analytical models to more complex integro-differential models leading to numerical simulations. In this paper we will focus mainly on the analytical models, which lend themselves more immediately to a simple assessment of HC performance.

In general, a successful model must include all relevant processes within a cathode, together with their dependence upon parameters such as propellant flow rate and the potentials of external electrodes. These processes include the formation of the internal plasma, the emission of the electrons, which pass eventually to the keeper electrode and anode, and the conduction of those electrons through the orifice. At the more detailed level, the model should be able to explain the generation of high-energy ions and of the observed significant levels of discharge noise and oscillations over a wide range of frequencies[19,39]. Clearly, no model has yet accomplished all of these objectives, but good progress has been made.

Analytical Models

One of the earliest models of HC operation is the one developed by Siegfried and Wilbur in the 1980s[40,41]. The analytical formulation is based on the concept of an idealized "ion production region," defined as the volume circumscribed by the emitting portion of the insert. This model was originally developed for mercury HCs, but could be easily adapted to xenon as a propellant. One of its limitations is that the electron temperature cannot be calculated, so that an assumption has to be made from experimental data.

Another model, developed by Katz *et al.*[42,43], focuses on the tiny orifice region. This is treated as a cylinder containing a homogeneous neutral plasma with a thin wall sheath. Such an assumption is justified by the fact that, although many times larger than the Debye length, the orifice extends for only a few mean free paths for electrons, ions or neutrals. In this model too we need to make an assumption about the temperature of the electrons entering the orifice from the insert region. The model has been recently used to estimate the performances of a HC[44] and of a gridded, HC-based ion microthruster[26]. The fundamental information is that the HC plasma production is controlled by the ion current. Most of the ions generated in the orifice cannot escape through the keeper aperture without recombining on cathode surfaces[44].

A third model, by Salhi and Turchi[45], is the only one based on a purely analytical formulation founded on first principles. This model has been expanded to incorporate some differential equations solved numerically[46]. A simplified version has also been presented by Turchi and Salhi[47] and is discussed in another section of this paper.

Numerical Models
A HC model involving the numerical solution of a system of differential and integral equations has been developed in a collaboration between Centrospazio, MAI and RIAME MAI[48].

A viscous compressible code with a reacting gas capability has been used in a simplified model of the flow in a HC at the University of Southampton by Murray, Tutty and Gabriel[49].

Jugroot and Harvey at Imperial College have recently performed numerical simulations of the flow in the interior and in the plume region of a HC, using a 3D Navier-Stokes continuum code and a direct simulation Monte Carlo (DSMC) program[50].

A HC model for the case of a low-pressure arc has been developed recently by Kennedy[27]. It consists of a set of analytical, integral and differential equations, which need to be solved, in general, in an iterative way.

Physical Conditions
Most of the models discussed above require for their application certain information concerning the physical conditions within and immediately outside the cathode. As well as propellant flow rates, voltages, currents and wall and tip temperatures, which are relatively easy to measure accurately, other parameters of interest concern the plasma regions on both sides of and within the orifice. Owing to the very small dimensions of these regions, very little experimental information is available and, as pointed out above, estimates are often necessary from sparse data.

Jack, Patterson and Fearn[19] took measurements of the external plasma characteristics with a cylindrical Langmuir probe located 10 mm downstream of the keeper orifice in a HC-keeper-anode configuration essentially identical to that described above[10]. For a T5 HC, with anode currents below 1 A, the electron temperature T_e went above 4 eV and the electron number density n_e was of the order of 10^{11} cm^{-3}. For a T6 HC, T_e decreased with mass flow rate and increased with discharge current, reaching 5 eV for currents above 15 A, while n_e was of the order of 10^{12} cm^{-3}. The electrons were shown to have, to a good approximation, a Maxwellian distribution.

Monterde, *et al.*, took measurements of the external plasma[23] and also, which is much less frequent, of the plasma within a HC[51]. The HC was of the type designed for the UK-25 ion thruster, operating in an open-keeper, anode-plate configuration. The plasma region between the keeper and the anode electrodes was investigated with a single Langmuir probe. Again, it was shown that the electrons have a Maxwellian distribution. Detailed scans gave a T_e between 0.3 and 0.4 eV, while n_e was of the order of 10^{11} cm^{-3}. These order-of-magnitude differences with respect to the results reported above[19] can be explained by the much higher mass flow rate employed. For example, at 10 A anode discharge current, ~4.5 mg/s[23] versus ~1 mg/s[19].

Using a monochromator and a photomultiplier, emission spectroscopic methods allowed the same investigators[51] to obtain measurements of the electron temperature and density of the internal plasma of a HC. The cathode type and discharge configuration were the same as above[23]. For a discharge current of 10 A and a mass flow rate of ~2 mg/s, the estimated values of T_e and n_e are ~1 eV and of the order of 10^{14} cm^{-3} respectively. Therefore, the HC internal plasma does not satisfy either the conditions (McWhirter) for local thermodynamic equilibrium (LTE) or for the coronal model (Bates)[23]. The corona-radiative model appears to be a more realistic representation. Numerous discrete emission lines associated with Xe, Xe^+ and Xe^{2+} were observed in the recorded emission spectra. However, Xe^+ dominates. This is consistent with computer simulations performed by the same authors, for T_e~1 eV.

Preliminary HC Thrust Assessment

We now try to assess the thrust obtainable from a HC, making use of a critical review of relevant experimental results and theoretical models. In this, we need to concentrate on ion extraction and acceleration mechanisms, rather than electron emission, which is the usual area of concern for HC theories.

Models

A simplified model proposed by Turchi[47] shows that, even if ionisation is excluded, HCs could make good electrothermal micro-thrusters. Of course, this will entail the use of low atomic weight propellants if higher specific impulse is needed. On the contrary, in ion thrusters high-atomic weight propellants, mainly xenon, are preferred, in order to increase the thrust density. Cathodes have therefore been extensively operated with "heavy" noble gases, usually Xe, but also including Kr and Ar, since the 1970s[52,53].

The lighter noble gases, Ne and He, have also been studied[22], but to a lesser extent, in connection with fundamental physics investigations together with this possible application. Unpublished work by Davis, Charlton and Newson of Mullard Ltd[22] investigated the use of most of the rare gases in a T5 thruster HC and concluded that the cathode worked reasonably well on all gases, but the operating potential increased with ionisation potential, as might be expected. Edwards and Gabriel also examined the possible use of alternative propellants[54]. However, HCs reportedly also work successfully with hydrogen (H_2) and ammonia (NH_3), which are the "light" propellants used in quasisteady magnetoplasmadynamic (MPD) thrusters[55].

Numerical computations performed by Jugroot with a continuum Navier Stokes 3D solver[50] show that the neutral xenon flow, heated by a HC insert at a temperature of 1000 K, reaches a Mach number M=0.9 in the orifice. The flow leaving the cathode expands but does not keep on accelerating to form a supersonic jet. Instead, it decelerates and disperses. This is due to the viscous mixing occurring in the coupling plasma volume, and would not happen without sufficient background pressure to form shear layers and retard the flow.

Experiments

Notwithstanding all the differences in experimental setup and conditions, some interesting common features can be observed by comparing various results.

Even if the experiments by Latham *et al.*[6] were performed with a T6-type HC and those by Crofton[4] with a T5 HC, a comparison of the results is nevertheless possible. We assume, as is reasonable due to the high current densities[26], that the processes taking place in the orifice region govern the amount of plasma flowing from a HC. We can therefore expect that different cathodes at similar discharge currents and equivalent flow rates, having similar ratios between current densities and charge carrier densities in the orifice, will behave in a similar way. It is important to notice, though, that a smaller orifice diameter will give rise to a higher orifice impedance and, consequently, higher temperatures[13]. In this light, we can compare OP 1 from Crofton[4] with the data from Figure 5 (Culham)[6], as they both have a discharge current to equivalent current ratio (and therefore a current density to equivalent current density ratio in the orifice) ~15. We see that in both cases the ion energy spectrum presents a peak at ~35 eV and an appreciable amount of ions with energies above keeper voltage. The keeper voltage is, however, 26 V in the first case[4] and 42 V in the second[6].

It is important to note that the scaling used in this paper is only tentative, and the authors are aware of its inadequacy. Other possible ways of correlating the operation of different HCs are being considered. Taking into account the energy available to ionize a particle flowing through the orifice per unit time, even neglecting the dependency of dissipation in the orifice on temperature through the resistivity, leads to more complicated scaling expressions. It is felt that accurate comparisons between HCs with widely varying geometries and operating conditions would be beyond the scope of the present analysis.

Calculated Performance

In order to gain an idea of the actual thrust performance we can expect from a HC, we can analyze in more depth the experiments by Crofton[4] and Latham *et al.*[6].

OP 5 shows a relatively high ion current extracted. From Figure 2, taking into account the RPA area (1.0 cm^2) and integrating the ion flux over the angular distribution, we obtain 3.7 mA of ion current being exhausted. For a MFR of 29 mA equivalent current of 100% singly ionized xenon, this corresponds to a mass utilization ~13% and is consistent with Crofton's estimate of ~10% for OP 2. The two points correspond to similar, but not identical, conditions, having respectively a discharge current to equivalent current ratio of ~45 and ~53.

The high level of Xe^{2+} observed in the plume suggests that full ionization is approached near the cathode orifice for orifice current densities ≥ 5000 A/cm^2 at MFR = 0.03 g/cm^{2}s of xenon. This corresponds to an electron efflux to atomic particle efflux ratio of ≥ 20[4,5]. OPs 5 and 2 amply satisfy this condition.

From Figure 2 we see that the contribution to the thrust of the ions at $\phi > 60°$ will be negligible, especially considering that the ions at small ϕ are more energetic[4]. From Crofton, let us assume that the ion kinetic energy varies linearly from 50 eV for $\phi = 0°$ to 20 eV for $\phi = 60°$. This is a crude approximation, but it is consistent with the data reported in Figures 7 and 8[4]. Energies of the same order of magnitude were also measured at Culham for similar operating conditions and even for much higher currents, as shown respectively in Figures 5 and 6[6], but only on the HC axis. Knowing the angular distribution of ion flux, from Figure 2[4], by performing again a discrete integration we can calculate the axial kinetic energy and thrust. For OP 5 we obtain a thrust of ~32 μN. The thrust density on the centerline is ~0.12 μN/ cm^2.

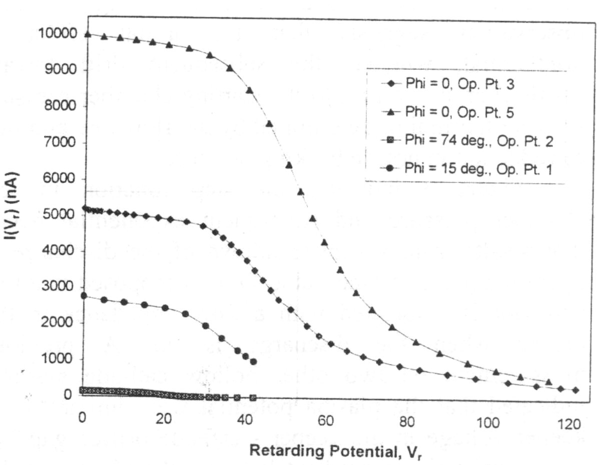

Figure 7 – RPA current vs. retarding potential (Aerospace Corp. data)[4].

By operating a T6 HC with the same ratios mentioned above, but at a current 5 times higher than in OP 5, i.e., 6.5 A discharge current and 145 mA equivalent current, we should be able to obtain ~160 μN of thrust from the ions. As already mentioned, such a simplistic scaling is, in all likelihood, incorrect.

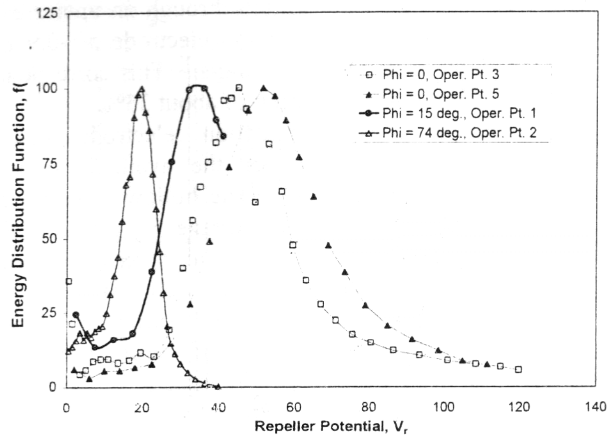

Figure 8 – Ion energy distribution function (Aerospace Corp. data)[4].

If a different approach is adopted and the curves resulting from the experiments performed at Culham (e.g., Figure 6) are integrated with respect to ion energy, the total ion current density is obtained as a function of energy. Dividing by the electron charge and multiplying by the ion mass gives the mass flow rate of ions per unit area as a function of energy. If this is then multiplied by the ion velocity (from the knowledge of ion energy and mass), the thrust of ions at that energy, per unit area, can be derived. Further integration would then yield the thrust.

This approximate calculation has been carried out for several sets of data acquired by the Culham Laboratory. The results are much higher than those discussed above, perhaps indicating that this cathode was more effective as a thruster. Typical thrust densities were a few mN/cm^2 at the lowest flow rates (~3.6 mN/cm^2 for the 1 A keeper, 0.07 A equivalent current case of Figure 5) to a few tens of mN/cm^2 at the highest flows (~27 mN/cm^2 for the 10 A discharge, 1 A equivalent current case of Figure 6). The actual thrust, of course, will depend on the angular distribution of the ion flux, which is not known here. Measurements at Culham, in fact, were taken only on the centerline, with a compact RPA, as opposed to those by Crofton, who explored practically all angular positions. Highly localized sputtering damage on the baffle, however, seems to suggest, even if only qualitatively, a pretty collimated ion beam, with a tight energy distribution.

Unfortunately, it has not been possible to check the accuracy of the actual numbers on the energy spectra.

They seem high compared to the RPA trace reported on the paper. The actual acceptance area of the particular RPA used is unknown, the only information being that it was fitted in a 6-mm diameter hole, but it should be, in all likelihood, not much less than 0.5 mm^2. All this casts a doubt over the validity of the above assessment, leading us to suspect that we might be grossly overestimating the obtainable thrust, even by orders of magnitude.

To the ion thrust derived in this way we have to add the electrothermal contribution given by assuming that the remaining ~87% of the flow is exhausted as neutrals. Using Turchi and Salhi's[47] simplified model, which considers the heavy particle flux not substantially ionized, we can have a first crude estimate. If just the enthalpy of the flow is fully converted into directed kinetic energy, neglecting the plume divergence and other losses, we can write:

$$\frac{5}{2}\frac{m}{m_{Xe}}kT_h = \frac{1}{2}m{v_e}^2$$

where k is the Boltzmann's constant, T_h the heavy-particle temperature and v_e the exhaust velocity. This yields for the exhaust velocity:

$$v_e = \sqrt{\frac{5kT_h}{m_{Xe}}}$$

The thrust and specific impulse are then:

$$F = mv_e \quad ; \quad SI = \frac{v_e}{g}$$

The temperature of the outer HC walls is generally around 1400 K. If we assume, quite conservatively, that the inner wall is only~100 K hotter and that the heavy particles inside the HC are in thermal equilibrium with the walls, which is not an uncommon assumption[41], we can take T_h = 1500 K. We thus obtain, for xenon, v_e = 689 m/s. At a MFR of 0.2 mg/s, this generates thrust of 138 µN and a specific impulse of 70 s. From these numbers it is evident that a "heavy" propellant like xenon is not a good choice for an electrothermal thruster, as could be expected.

In the vacuum of space we can expect a good expansion of the plume, yet we will not actually have a full conversion of the enthalpy into useful kinetic energy, if only for the fact that the plume diverges. We can correct the result we have just obtained by assuming that the shape of the whole plume resembles the ion flux angular distribution. This is also quite a simplistic assumption. In this way we obtain an electrothermal contribution to the thrust of ~100 µN, with a 72% thrust efficiency and a specific impulse of just ~50 s.

Our HC could then give a total thrust of ~260 µN at 6.5 A. At a MFR of 0.2 mg/s, this corresponds to a SI of ~130 s. This would not make a very efficient thruster. In order to improve the performance, we could attempt to increase the extraction of ion flux, if we want to build a micro-ion thruster, or utilize propellants with lower atomic weight, if we instead want to realize an electrothermal thruster.

Of the other noble gases, only helium and neon are "light" enough to actually make a difference in the performance, but their ionisation potentials are much higher: 24.6 and 21.6 eV, respectively, versus 12.1 eV for xenon. Hydrogen has been used as a HC propellant, even if in different devices[55]. Its performance was investigated by Salhi and Turchi[47] for an application like the one we are discussing here. They assumed T_h = 2500 K, but even maintaining our conservative figure of 1500 K for hydrogen as well, we obtain a specific impulse of ~800 s. By applying the thrust correction calculated above, say a ~70% efficiency, we still have SI ~ 560 s, which is in the low range of arcjet performance. The use of hydrogen could cause chemistry-related problems that would probably reduce lifetime. With helium we might obtain a lifetime comparable to that resulting from the use of other noble gases, even if at a higher operating potential. In this case we would of course obtain a specific impulse of ~280 s, still comparable to that of some chemical thrusters.

Assuming that, even for a hydrogen HC, we have the same type of operation as with xenon, we might still achieve a ~10% mass utilization, while ~90% of our MFR is exhausted as neutrals. In order to estimate the ionic thrust, we now make another extremely crude assumption, that is we use the same energy and mass flow distribution as for xenon. With a propellant as light as hydrogen, we now have a much higher ion velocity (and therefore SI), by a factor equal to the square root of the ratio of atomic weights. The ion momentum, though, will be lower by the same factor and thus the thrust will be reduced.

Preliminary Thrust Measurements

Tentative experiments were very recently performed at QinetiQ, aiming at a first rough evaluation of the thrust obtained from a hollow cathode. To the authors' best knowledge, they represent the first thrust measurements ever actually performed on a HC. These were indirect measurements of a T6 cathode ion momentum flux, carried out with a target balance. They are particularly interesting in that this model, intended for an HET, is practically identical to the one at the University of Southampton. It has a 1.3-mm-diameter orifice, much larger then the one used in the Culham experiments, where a T6 HC was also employed.

A thrust of ~0.2 mN was measured with no discharge at a mass flow rate of ~1 mg/s. With the discharge on, the thrust went up in steps as the current was increased, with a maximum of ~0.5 mN at 10 A discharge current and ~1 mg/s MFR. Lower values of the MFR produced lower values of thrust, as is to be expected, but their effect on the ionization fractions was not investigated at this preliminary stage.

These recent measurements seem to indicate that the assessment reported above, from Culham data in the literature, is indeed too optimistic. This is probably true, even if a smaller orifice diameter would entail higher current densities and therefore, conceivably, a stronger electromagnetic acceleration and higher ionization fractions. The two devices could thus be operating in different regimes. The specific impulse at 10 A discharge current is, in fact, only 50 s, corresponding to our estimate for a purely electrothermal acceleration. This would suggest that the discharge here is mainly heating the gas, but we are in a regime were no significant production of high-energy ions occurs.

Again, we need to stress that these are tentative, preliminary experiments, where no effort was made to optimize the performance of the device. Nevertheless, they are the first measurements ever actually performed and confirm that a significant thrust can be obtained, even if at a very low SI. No accurate estimate of the error incurred in the measurement is available, but it is felt that it might be as high as 50%.

Future HC Thrust Measurements

Hollow Cathode

The cathode that will be used in the experiments at the University of Southampton is based closely on the discharge chamber cathode of the T6 thruster, but this particular version is intended for an HET, like the one used in the preliminary experiments at QinetiQ. It is capable of operation for long periods at currents of up to 30 A. It presents a slightly larger orifice than a standard T6 HC, with a 1.4 mm diameter countersunk at an angle of 45° to a depth of 1 mm. The keeper configuration is of the enclosed type, with a cathode-to-keeper gap of 2.5 mm.

Target Design and Calibration

The various methods for the measurement of thrust fall into two general categories: direct methods, where the thruster is suspended on a thrust balance, the displacement of which is measured by a sensor, and indirect methods, where the thruster is fixed and the displacement of a target balance, which is impacted by the thruster exhaust, is measured.

These latter techniques present several advantages over direct methods. The sensitivity of the balance is inversely proportional to the weight of the moving part and, if the thruster is mounted on it, this may be quite heavy, which also causes frictional losses due to the suspension. Unless the whole propulsion system is mounted on the balance, as could be the case with an ablative pulsed plasma thruster (APPT), electric power cables, propellant feed lines and, possibly, cooling flow lines will cause a high motion resistance[56,57].

In general, an indirect system is independent of the specific thruster configuration and allows the measurement of the performance of different propulsion systems without changes to the balance and consequent recalibration[57]. A potential interpretation problem is caused by the imperfect knowledge of the interaction processes between the target and the plasma/ion beam. Problems concern the degree to which momentum is transferred to the target and the angular reflection processes. Impacts, in general, will neither be completely elastic nor inelastic. Another possible problem is ion sputtering, although this might not be too significant at the energy levels considered here, for which some information is available. Metals like iron, copper and aluminum have comparable yield factors[58]. A way to assess and reduce these errors will be to use different surface roughnesses and maybe materials. Experiments can be also devised to estimate particle reflection from the target. At the very least this system should be good for comparative tests.

An interesting target design was devised in the past to minimize the effect of rebounding particles and is shown in Figures 9 and 10[57,59]. Here the particles impinge on the bottom aluminum plate, which has a conical shape in order to scatter them as effectively as possible toward the discs that make up the sides of the cylindrical target. After a series of collisions, the particles will leave the target with an essentially radial momentum. The open area normal to the radial direction is, in fact, many times larger than that normal to the axial direction.

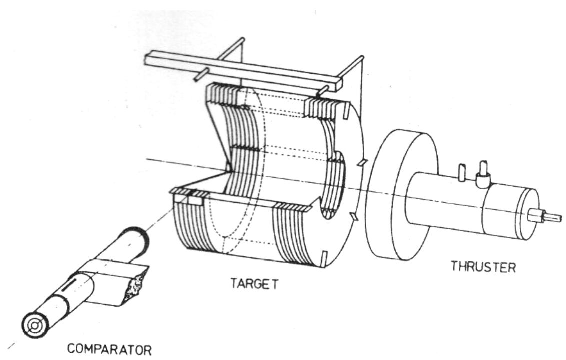

Figure 9 – Cylindrical target[59].

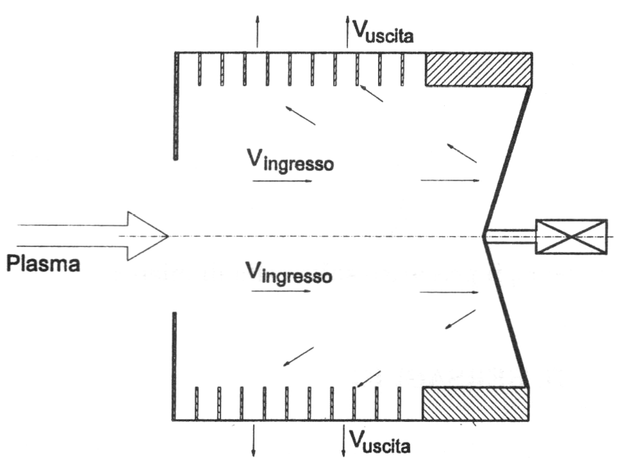

Figure 10 – Cylindrical target section and operation[57].

The target selected for the initial part of the investigation campaign at the University of Southampton is a planar one, part of a cantilever beam. A square shape has been chosen for simplicity, the only requirements on the geometry being symmetry with respect to the thruster axis and the interception of most of the particles from the exhaust. As a material, aluminum has been selected for ease of fabrication, good electrical conductivity and low Young modulus, which gives a high sensitivity. This is given by[60,61]

$$\frac{D}{F} = \alpha \frac{L^3}{Ebh^3}$$

where D is the displacement of the free end of the beam, F is the load applied to it, E the Young modulus and L, b and h, respectively, the length, width and thickness of the beam. The parameter α is a proportionality coefficient dependent on the location and modalities of load application and also on the beam shape and proportions. A photograph of a prototype target is shown below, in Figure 11.

Figure 11 – Aluminum target and insulating mount (ruler is 30 cm).

It is to be noted that, being the target much wider than the thin parts of the beam, this latter will only intercept a negligible part of the flow. Because of its width, the target is also much more rigid. Additional plates could be fastened to it in order to further increase its stiffness. This would also make it easier to vary the surface characteristics. Our system may then be modeled as a simple cantilevered beam with a load applied at the target centre, the actual distribution of the load on the target being unimportant and the load on the thin beams being negligible. The part between the target and the free end, being unloaded, will not inflect, but will give us a longer "arm" and therefore a greater sensitivity. The length *L* is limited by the size of the vacuum chamber (0.5 m diameter) to 40 cm. By varying *b* and *h*, the sensitivity can be increased up to ~1 μm/μN. A trade-off is necessary between a high sensitivity on one side and robustness and stability toward mechanical and thermal perturbations on the other. A "flimsy" target, while extremely sensitive, will also be easily damaged and might be deformed by thermal expansion through contact with the HC plasma.

Even if the theory of beams is well established, it will be necessary to proceed to a direct calibration of the target. This can be accomplished by means of precisely measured weights. By applying known forces to targets with the same shape but different thickness *h*, it will be possible to verify the accuracy of the theoretical expression for the deflection of the beam.

The target will also be used as a Faraday plate. By biasing it at different potentials, we will be able to collect both neutrals and ions (target biased slightly negative) or only neutrals and electrons (target with increasingly strong positive bias to eventually repel all the ions). A possible problem that should be addressed here is secondary electron emission.

We can thus estimate total and ion momentum flux and ion current. From the ion current the ion mass flow rate can be calculated by assuming for example, as a first approximation, singly-ionized ions. From these and knowledge of the total mass flow rate, specific impulse and ion average velocity can be assessed.

We could also replace the target with an RPA, in order to accurately analyze the ion energy distribution. This would give an independent assessment of thrust, which is a very desirable objective.

It would also be important to characterize the plume structure by using Langmuir probes. In particular, end-effect Langmuir probes[62,63,64,65] would allow us to assess the direction of the ion velocity. This would be important to estimate how much of the efflux from the HC orifice we are actually intercepting with our geometry, which is another possible source of error to be reckoned with when using indirect thrust measurement methods.

Displacement Measurement

The accuracy of our thrust measurement is essentially dependent on the resolution with which we can measure the displacement of the free end of our beam. In order to measure the beam end displacement, we can use a capacitance gauge. Commercially available models have a resolution of a few nanometers[66]. As an alternative, we might use a laser vibrometer. This is an inherently noisy instrument, with a resolution of about 1 μm. We could borrow one from the Institute of Sound and Vibration Research (ISVR) at the University of Southampton.

We could also, eventually, develop our own measurement system. This could be a laser Michelson interferometer, similar to Princeton interferometric proximeter system (IPS)[67], or a laser "lever" with a segmented photodiode. Both these instruments can easily be built to achieve very low resolutions. The Princeton IPS has a 10-nm resolution[67]. This is the highest accuracy believed to be obtainable, much lower than the quarter-wavelength unit of displacement[68] and limited essentially by noise[67]. The resolution of the laser lever depends on the length of the optical path and on the characteristics of the segmented photodiode and of the light balance detection circuit, but can be made comparable with those of the other systems mentioned above with a careful design.

Conclusions

We are working on a thorough characterization of hollow cathode ion emission. An analysis of past experimental results by various authors seems to suggest that it should be possible to obtain an appreciable thrust at a reasonably high specific impulse, even if it is difficult to reach a definite conclusion from sparse data. Preliminary thrust measurements have been carried out. Even if only tentatively, they confirm that a significant thrust can be obtained even if at a very low specific impulse. This latter needs to be improved in order to make the hollow cathode competitive with other microthrusters.

Our calculations and experiments therefore emphasize the need for a more extensive data collection. New measurements of ion flux and thrust will be performed in order to assess the potential performance of a hollow cathode as a non-magnetic micro-ion thruster.

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