Thrust Characterization of a T6 Hollow Cathode

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Abstract: Using a target-based measurement system, the thrust produced by a T6 ion engine hollow cathode has been measured, with neon, argon, krypton and xenon as propellants, for discharge current values of 5-25 A, a wide range of mass flow rates and two different orifice diameters. The calculated values of specific impulse, which are higher for lower atomic masses, are generally in excess of those that could be attributed to heating a gas to thermal equilibrium with the walls. This seems to suggest, as a first hypothesis, an arcjet-like operation mechanism.

Nomenclature

b	=	beam width
D	=	target diameter
e	=	electron charge
E	=	Young's modulus
F	=	thrust
g	=	acceleration of gravity at sea level
h	=	beam thickness
I_{sp}	=	specific impulse
k	=	Boltzmann constant
L	=	beam length
m	=	atomic mass
$\dot{m}$	=	mass flow rate
P	=	optical path length
T	=	heavy-particle temperature
$\Delta\theta$	=	angular deflection
Δx	=	linear displacement

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I. Introduction

HOLLOW Cathodes (HCs) have been extensively investigated and tested. Although the physics of its operation is only partially understood, the HC is a space-qualified device, with a long proven life. In a Kaufman-type gridded ion engine, like the QinetiQ T6, HCs are used to produce the electrons that will ionize the propellant and for the neutralizer as well. A T6 cathode in an open-diode configuration, with an anode mounted in front of the orifice, is currently being investigated to determine the thrust that can be produced by the extracted plasma plume. Measurements have been taken, with several noble gases as propellants, using a target-based thrust measurement system.

II. Experimental Apparatus

The experiments described in this paper were carried out in the Astronautics Laboratory at the University of Southampton, School of Engineering Sciences, Astronautics Research Group, with a thrust measurement system specifically developed for that purpose.

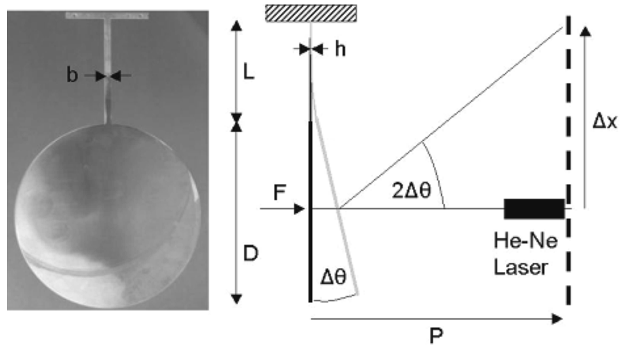

Figure 1. The CBT-LOL thrust measurement system.

A. Measurement System

A thrust measurement system has been developed at the University of Southampton. The HC plume impinges on a Cantilever Beam Target (CBT), mounted downstream of the anode. The target angular deflection $\Delta\theta$ is related to the thrust F by[1, 2]

$$\frac{\Delta\theta}{F} = \frac{6}{Ebh^3} L(L+D), \quad (1)$$

where E is the Young's modulus of the material used (molybdenum for this CBT) and the other symbols are illustrated in Fig.1, which shows a diagram of the system and a photograph of the CBT. $\Delta\theta$ is translated into a linear displacement Δx with a Laser Optical Lever (LOL), according to the formula[1, 2]

$$\Delta x = 2P\Delta\theta, \quad (2)$$

valid for small values of $\Delta\theta$ (exaggerated in Fig. 1), where P is the optical path length. F is therefore related to Δx by the expression[1, 2]

$$F = \frac{Ebh^3}{12PL(L+D)}\Delta x. \quad (3)$$

Δx is measured with a Hamamatsu S2044 Position Sensitive Detector (PSD), with a resolution of 600 nm, corresponding, in the present configuration (with an optical path length P~1 m), to a thrust measurement resolution of ~3 μN[1, 2].

B. Vacuum rig

The vacuum rig used in our experiments was described in previous papers[3, 4] and has undergone only minor modifications recently. It consists of a stainless steel cylindrical chamber, 0.5 m in diameter and 0.5 m long, pumped down to a pressure in the 10^{-7} mbar range with no flow and in the 10^{-4}-10^{-3} mbar during experiments by the use of a rotary and a turbomolecular pump connected in series. Oxygen and moisture traps are inserted in the propellant feed lines to enhance gas purity and avoid contamination of the HC insert.

C. Hollow Cathode/Anode Assembly

The HC currently under investigation was developed by QinetiQ for the T6 Kaufman-type ion thruster. Its basic features have essentially remained unchanged since the start of the program and are described, together with the physics of HC operation, in various papers[5, 6]. The initial orifice diameter of 0.5 mm, with which most of the measurements reported in this paper were taken, was smaller than those used in the majority of previous investigations of the behavior of this kind of device. The HC orifice diameter was later enlarged to 1.0 mm. The HC was operated in an open diode configuration, without using a keeper electrode as in the majority of previous investigations in the literature. A circular anode, machined from a 100 mm diameter steel disc, is mounted on insulating supports about 2 mm in front of the HC tip. The anode presents a large (20 mm diameter) central orifice, to allow the plume to reach the target relatively unimpeded.

III. Results and Discussion

Experiments have shown that it is possible to operate a T6 HC in this particular open-diode discharge configuration at values of mass flow rate between ~0.25 mg/s and 4-5 mg/s using argon, krypton and xenon as propellants and producing several mN of thrust at values of specific impulse exceeding, in some cases, 500 s. Operation with neon proved more problematic, and breakdown was actually achieved in a more limited number of cases. The discharge was often unstable, with a tendency to shut down sometimes as conditions were varied. Therefore, thrust measurements with neon as a propellant were performed in a narrower range of mass flow rates and for fewer values of discharge current. As they are not enough to show significant trends, they are not presented in this paper.

A. Thrust Measurements

The thrust generated by the T6 HC was measured for values of the discharge current between 5 A and 25 A, and for a wide range of mass flow rates. A part of these measurements is shown in the plots below. Fig. 2 shows that the thrust increases with increasing discharge current and increasing mass flow rate. This trends, represented here for xenon, have been observed with all of the propellant gases.

Fig. 3 shows a comparison of the different values of thrust generated when operating the HC at maximum current with three different propellant gases. At very low mass flow rates it was not always possible to maintain a 25 A discharge. The current values are, anyway, always higher than 20 A. We can see that, in general, the performance improves with decreasing atomic mass.

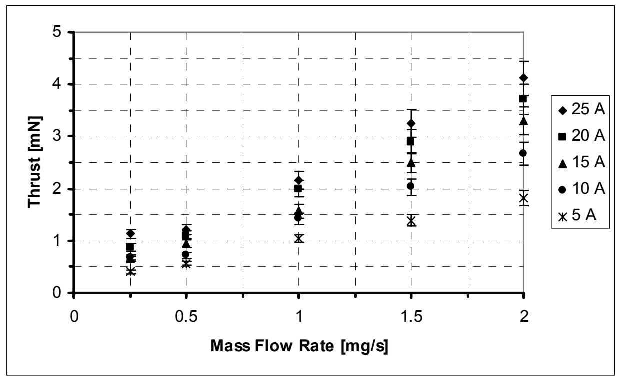

Figure 2. Thrust with xenon as propellant.

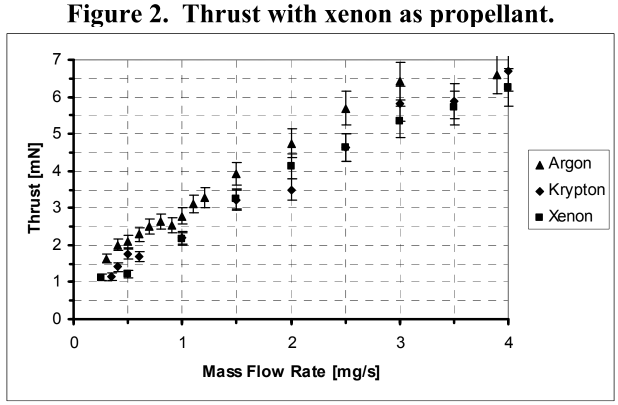

Figure 3. Thrust with different propellants.

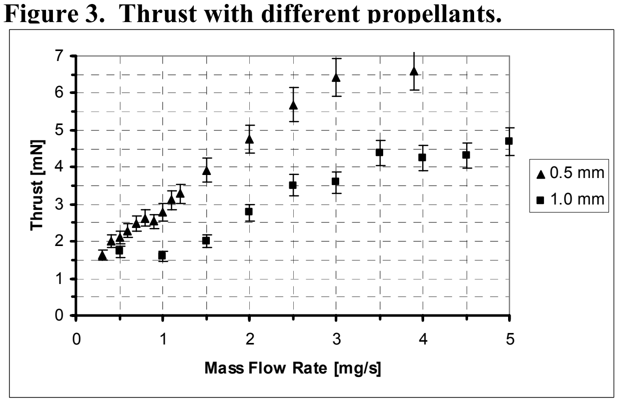

Figure 4. Thrust for two different orifices with argon.

The measurements in Figs. 2 and 3 were taken with the initial HC orifice diameter of 0.5 mm. The orifice was later enlarged by drilling out to 1.0 mm diameter, and new thrust measurements were taken, for the moment only with argon as a propellant. From Fig. 4 we can see that the thrust at maximum discharge current is lower with the larger orifice diameter. This could be due to the fact that, for the same value of discharge current, a larger orifice area corresponds to a lower current density in the orifice.

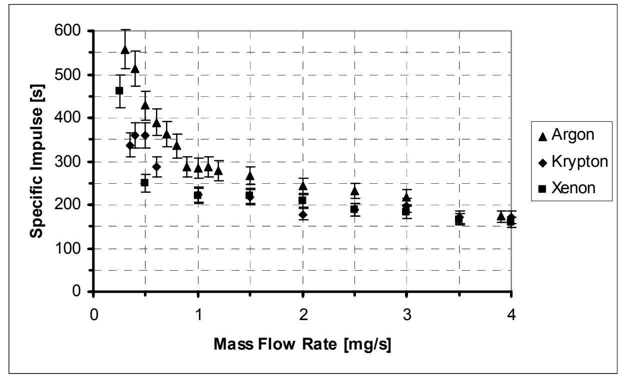

Figure 5. Specific impulse with different propellants.

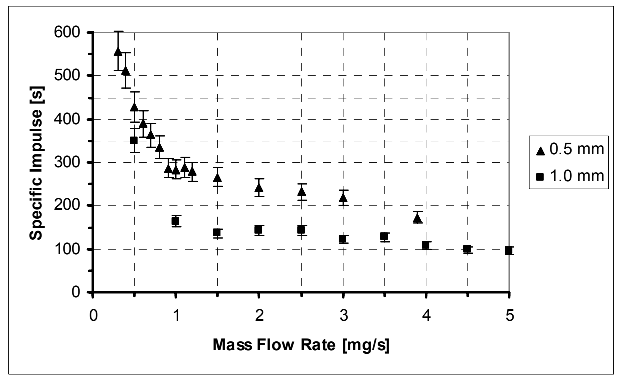

Figure 6. Specific impulse for two different orifices with argon.

B. Specific Impulse

The specific impulse I_{sp} is, in general, higher for lighter gases, as shown in Fig. 5. The expected rough inverse proportionality to the square root of the atomic mass may be somehow mitigated by a penalty due to the higher ionization potential of lighter atoms.

The measurements in Fig 5 were taken with the initial HC orifice diameter of 0.5 mm. Fig. 6 shows the effect of drilling out the orifice. Again, it is quite clear that a larger orifice causes degradation in performance, with lower values of specific impulse for the same discharge conditions, probably due to lower current densities in the orifice.

The measurements shown in Figs. 5 and 6 were taken at approximately constant current (~25 A, 20-25 A for very low mass flow rates). The discharge voltage was roughly constant (10-13 V) for mass flow rates higher than ~1 mg/s, corresponding to stable spot mode[7]. For mass flow rates lower than ~1 mg/s, corresponding to noisy, unstable plume mode[7], the discarge voltage increased rapidly, in some cases above 50 V. Therefore, the discharge voltage to mass flow rate ratio increases with decreasing mass flow rate. This may explain the corresponding increase in specific impulse.

C. Thrust Generation Mechanisms

The above mentioned I_{sp} values are greater than would be expected for a device just heating a gas, with heavy particles in thermal equilibrium with the wall. Even assuming full conversion of the flow enthalpy into directed kinetic energy, neglecting the plume divergence and other losses, we would in fact obtain[4]

$$I_{sp} = \frac{F}{\dot{m}g} = \frac{1}{g}\sqrt{\frac{5kT}{m}}\,, \tag{4}$$

where $\dot{m}$ is the mass flow rate, g the acceleration of gravity at sea level, k the Boltzmann constant, T the heavy-particle temperature and m the atomic mass. Equation (4) yields, for argon at 2000 K (a temperature probably higher than that of the insert wall), a value of I_{sp} ~150 s, which is an upper limit, unattainable in practice because of various kinds of losses. Thus, our results indicate a contribution to the thrust other than simple thermal heating through equilibrium with the HC wall, as in the case of a resistojet. This thrust contribution could be attributed to the presence of energetic neutrals, which could be produced by charge-exchange collisions with ions, provided that these were of higher than thermal energies. If the neutral-neutral collision frequency were high enough, thermalization would occur and the propellant gas would actually be hotter than the HC walls. The performance degradation shown by the HC with the enlarged orifice operating with argon as a propellant could suggest that Joule heating plays an important role as well. By doubling the orifice diameter, in fact, for the same values of discharge current the current density in the orifice decreases by a factor of four.

Our HC thruster, therefore, would operate in a fashion similar to that of an arcjet, with an inner plasma column much hotter than the walls. In such a case, the I_{sp} would be greatly increased by the use of a propellant with lower atomic mass, as shown in our results. For certain values of discharge current and mass flow rate, it could even be akin, at least partially, to a magnetoplasmadynamic arcjet, with electromagnetic acceleration followed by some thermalization produced by collisions. Unfortunately, it has proved very difficult to achieve stable operation, even in plume mode, for the very low values of mass flow rate likely to be required to attain this regime, which also needs high current.

IV. Conclusion

A measurement system has been developed, through which the thrust produced by a T6 thruster HC operating with neon, argon, krypton and xenon as propellants has been evaluated at different mass flow rate and discharge current conditions, and for two different orifice diameters. Few investigators in the past have performed experiments with such a variety of propellants[8]. The measurements obtained correspond to I_{sp} values well above those that would be expected from a device simply heating a propellant gas in equilibrium with normal HC operating wall temperatures, suggesting an arcjet-like operation mechanism. If values of I_{sp} can be obtained that are at least partially competitive with other types of microthruster, then a whole host of potential applications may be envisioned. In a satellite, for instance, the use of a HC thruster for attitude control could be convenient, even at modest values of I_{sp}, in conjunction with an ion engine for drag compensation and maybe orbit raising, as these two devices could share the same propellant and power conditioning subsystems. This would avoid the need for a separate chemical propulsion system. Such an “all-electric spacecraft” would be considerably lighter and simpler, due to a reduced number of subsystems and to propellant mass savings made possible through the higher I_{sp}.

References

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