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THRUST MEASUREMENTS OF A HOLLOW-CATHODE DISCHARGE

by Aaron Snyder and Bruce A. Banks
Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

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SUMMARY

Thrust measurements of a hollow-cathode mercury discharge were made with a synthetic mica target on a torsion pendulum. Thrust measurements were made for various target angles, tip temperatures, flow rates, keeper discharge powers, and accelerator electrode voltages. The experimental thrust data are compared with theoretical values for the case where no discharge power was employed. For a tip temperature of 1110 K and an equivalent neutral flow rate of 47 milliamperes, measured cathode thrust values between 2.6×10^{-5} and 5.2×10^{-5} newton were obtained for no keeper discharge. Operation at the same conditions but with a discharge of 0.75 ampere and 19 volts resulted in a 28-percent increase in thrust.

INTRODUCTION

In recent years, hollow cathodes have been widely used on Kaufman ion thrusters, for both neutralizer and main cathodes (ref. 1). Because a hollow cathode produces thrust, it is of interest to know the thrust magnitude under typical operating conditions. Knowledge of the thrust level would allow determination of how much the thrust vector is changed due to the thrust of the neutralizer. If a hollow cathode were designed and operated to produce sufficient thrust, it could be used as a micro thruster.

This report presents thrust target measurements of the discharge of a hollow cathode for various operating conditions, with mercury as the propellant.

APPARATUS AND PROCEDURE

The cathode used for all the data presented herein is shown in figure 1. It consisted of a 3.2-millimeter-diameter, tantalum tube with a barium carbonate coated insert and had a 0.25-millimeter-diameter orifice in the thoriated tungsten tip. The tantalum ring

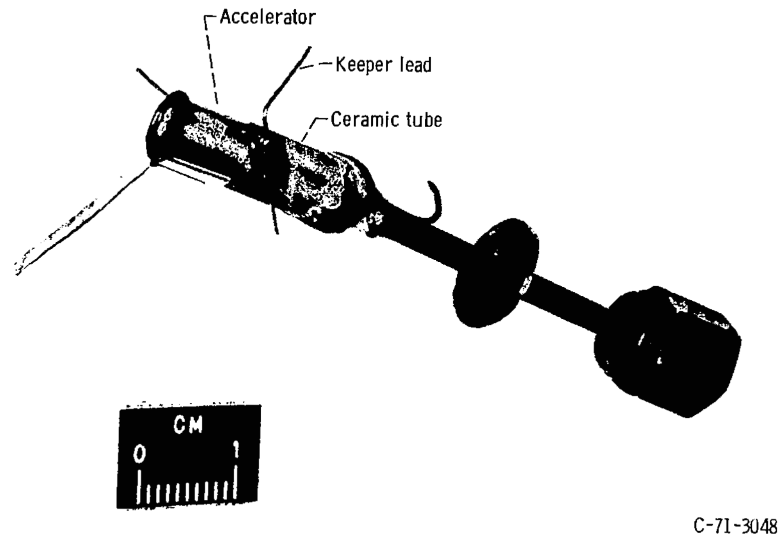


Figure 1. - Cathode-keeper-accelerator system.

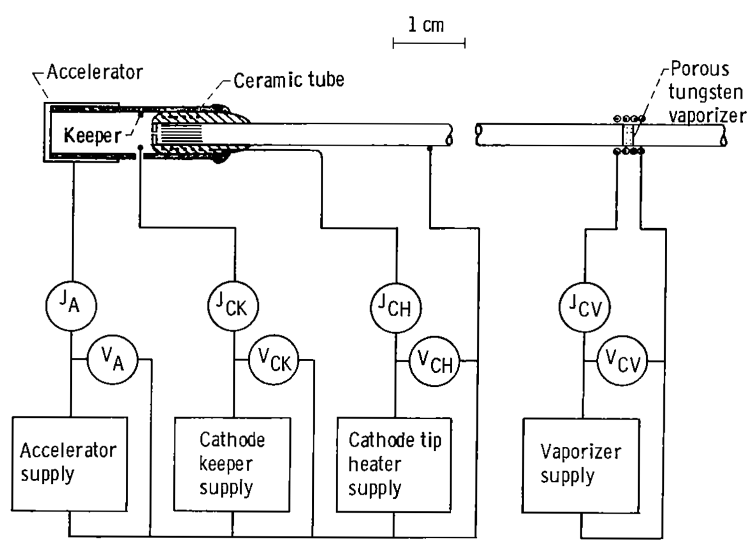
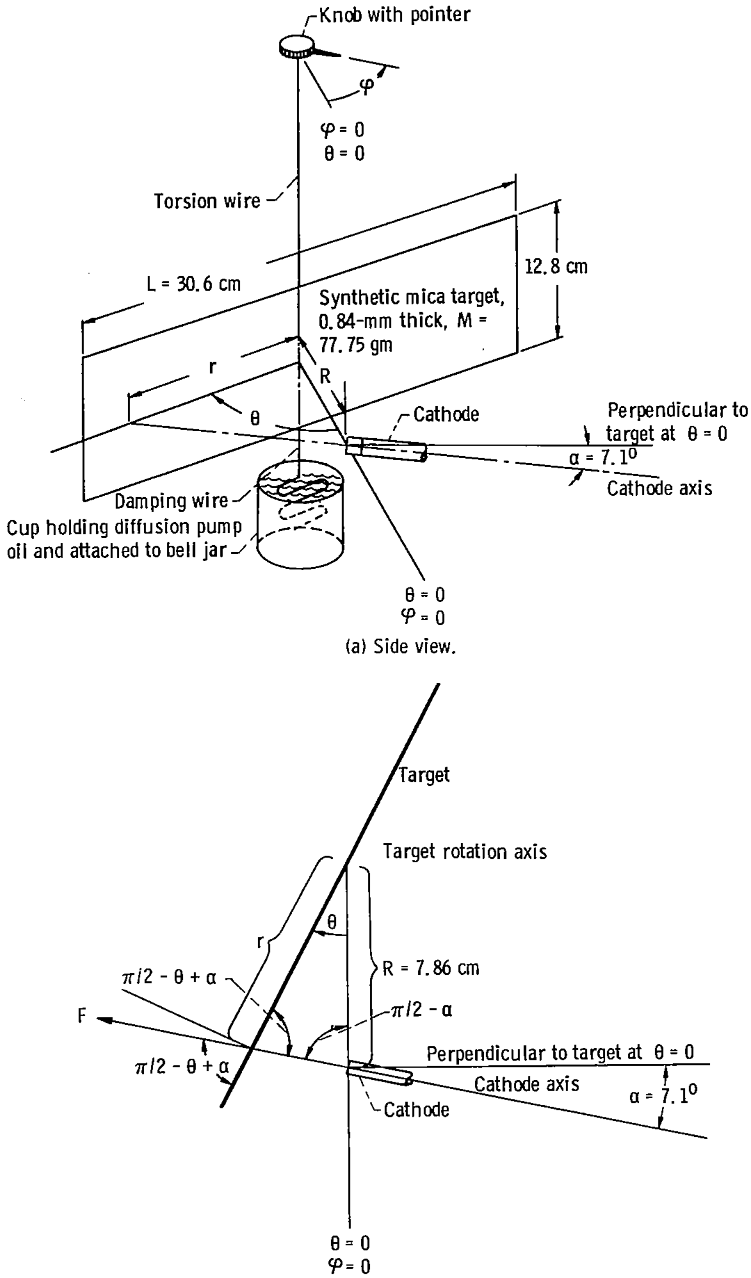


Figure 2. - Section view of cathode-keeper-accelerator system and electrical schematic.

keeper was enclosed inside a ceramic tube with the keeper electrical leads coming through small holes in the ceramic tubing (figs. 1 and 2). An additional electrode was placed downstream of the keeper ring to investigate the effects of acceleration of ions and/or electrons on the measured thrust. This accelerator electrode consisted of a tantalum ribbon wrapped around the outside and extending slightly beyond the end of the ceramic tube. It could be biased positive or negative with respect to the cathode tip. The mercury flow rate was controlled by a porous tungsten vaporizer and was measured



(a) Side view.

(b) Top view.

Figure 3. - Torsion pendulum and cathode geometry.

by observing volumetric displacement of mercury in a glass flow tube. Cathode tip temperature was measured with an optical pyrometer by looking through the plasma and assuming the surface of the tip to be a black body.

Thrust was measured with a torsion pendulum which consisted of a synthetic mica rectangular target (30.64 cm wide, 12.78 cm high) suspended by a 0.076-millimeter-diameter tungsten torsion wire approximately 43 centimeters long (fig. 3). The torsion pendulum was damped by means of a bent piece of wire which was partially immersed in a container of diffusion pump oil. The upper end of the torsion wire was connected to a rotatable shaft that passed through a vacuum seal. The equilibrium rotation angle θ of the target could be adjusted by turning a knob at the top of the bell jar. The orientation of the cathode system was such that when the target was rotated so that the accelerator was just touching the target ($\theta = 0$), the cathode axis was at an angle of α with respect to a perpendicular to the target, as shown in figure 3. Angle φ is defined with respect to the $\theta = 0$ angle and in such a direction that $\theta = -\varphi$ represents a condition in which there is no torsion in the wire. (All symbols are defined in the appendix.)

If the damping wire is removed and the target is virtually an undamped harmonic oscillator in the vacuum, the differential equation of motion for a target with a moment of inertia I is

$$I\ddot{\theta} = -K(\theta + \varphi)$$

where K is the torsion constant of the torsion wire. Thus, the period of oscillation τ is

$$\tau = 2\pi\sqrt{\frac{I}{K}}$$

and the torsion constant K is

$$K = \frac{4\pi^2 I}{\tau^2}$$

Therefore, the torsion constant K can be determined by calculating the moment of inertia I and measuring the period of oscillation τ (without damping, in a vacuum). The moment of inertia for a thin, rectangular sheet of length L and mass M is

$$I = \frac{ML^2}{12}$$

Thus,

$$K = \frac{\pi^2 ML^2}{3\tau^2}$$

If the cathode is exerting a thrust F on the target which is rotated to an angle θ (see fig. 3(b)) and if the upper end of the torsion wire is at an angle φ, then the equation

$$rF \sin\left(\frac{\pi}{2} - \theta + \alpha\right) = K(\theta + \varphi) = \text{torque on torsion wire}$$

describes an equilibrium position where the thrust of the cathode balances the force produced by the torque in the torsion wire. Using a trigonometric relation yields

$$\frac{r}{\sin\left(\frac{\pi}{2} - \alpha\right)} = \frac{R}{\sin\left(\frac{\pi}{2} - \theta + \alpha\right)}$$

Therefore,

$$r = R \frac{\cos \alpha}{\cos(\theta - \alpha)}$$

Substituting this equation for r into the equation describing the equilibrium position of the target yields

$$RF \cos \alpha = K(\theta + \varphi)$$

This neglects any additional thrust due to molecules bouncing back off the target (this will be discussed later). Thus,

$$F = \frac{K(\theta + \varphi)}{R \cos \alpha}$$

or

$$F = \frac{\pi^2 ML^2(\theta + \varphi)}{3\tau^2 R \cos \alpha}$$

The thrust measurement was found to be easier to make with the damping wire added. The period τ was measured before the damping wire was installed.

Because the target tends to increase the local pressure between it and the cathode for small values of θ, it was of interest to measure the thrust F as a function θ. Thrust measurements were made by calculating the twist in the torsion wire for various target angles and cathode operating conditions. The target angle θ was measured with a sliding indicator. The indicator was alined with the target angle by sighting along the length of the target. The angle of rotation φ, of the top end of the torsion wire could be read directly, in degrees, as shown in figure 3(a). To allow measurement of the angle α, the initial ($\theta = 0$) position of the target was set by alining the plane of the target with a wire stretched along a selected diameter of the bell jar. The angle α was measured in relation to this reference wire. The twist ($\theta + \varphi$) in the wire was measured by recording the initial equilibrium position of the target (θ, φ, α) and then, after the cathode reached stable operation, measuring the new position of the target θ. By rotating the knob at the top end of the torsion wire through an angle φ, the initial equilibrium position of the target was changed, and the corresponding position angle of the target was measured. This procedure gave the measured thrust as a function of target angle θ. All cathode operating conditions were measured during each test.

It was necessary to adjust the tip heater power and vaporizer power to maintain constant cathode tip temperature and mass flow rate, respectively, because of the variation of these parameters with keeper discharge power. The same effect was not observed with accelerator power.

In this manner, thrust was measured as a function of target angle θ for the following three cases of cathode operation: (1) emission of the vaporized mercury with no discharge, (2) operating with a discharge, and (3) with a discharge and a potential applied to the accelerator.

DISCUSSION

Measured Force With and Without a Discharge

The measured force from the cathode is presented in figure 4 as a function of target angle θ for both the no-discharge and discharge cases of operation. The equivalent neutral flow rate was 47 milliamperes, the cathode tip temperature was 1110 K, and, for the discharge case, the discharge current J_{CK} was 0.75 ampere with a discharge voltage V_{CK} of 19 volts. Figure 4 indicates that the measured force is about 1.5×10^{-5} newton greater with a discharge than without. At a target angle of 10°, this increase represents about 28 percent of the measured force of the no-discharge case. For pur-

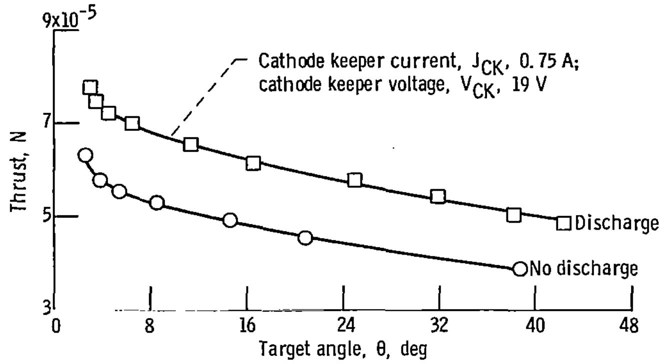


Figure 4. - Measured cathode thrust as a function of target angle for operation with and without a discharge. Cathode tip temperature, T_C, 1110 K; equivalent mass flow rate, 47 mA.

poses of comparison, the cathode thrust with a discharge (at 10° target angle) is 6.64×10^{-5} newton, which is small (0.24 percent) compared to the 2800×10^{-5} newton of the SERT II ion thruster (ref. 2). The change in measured force with target angle is probably a combination of two effects. First, as the target rotates away from the cathode, there is a reduction in local pressure which exists at small target angles because of multiple reflection off the cathode. This change in local pressure, which was observed during operation as a change in operating mode, would increase the measured force considerably at small target angles. Secondly, at large target angles the measured force was less because of a reduction in the amount of exhaust beam intercepted. As the target rotated outward from the cathode, it intercepted a decreasing fraction of the total emission. The measured force at small target angles, where the curves in figure 4 are nearly linear, was chosen as a realistic value of the actual force of the hollow cathode. A target angle of 10° was considered reasonable in light of these data, and all further tests conducted at a constant target angle were made at 10°.

Effect of Cathode Tip Temperature

The effect of cathode tip temperature on the measured force was tested for tip temperatures ranging from 962 to 1243 K. Figure 5 shows that the measured force without a discharge increased slightly with increasing tip temperature. The slight variation in measured force as a function of tip temperature is in agreement with the kinetic interpretation of temperature, expressed as

$$v = \sqrt{\frac{8kT}{\pi M_o}}$$

where M_o is the mass of the mercury atom, v is the average speed of the mercury atom, k is the Boltzmann constant, and T is the temperature. Therefore, the theoretical thrust of the cathode is

$$F_T = \dot{m}v$$

or

$$F_T = \dot{m}\sqrt{\frac{8kT_c}{\pi M_o}}$$

If the temperature of the molecules is assumed to be the cathode tip temperature, then the theoretical thrust should be proportional to the square root of tip temperature.

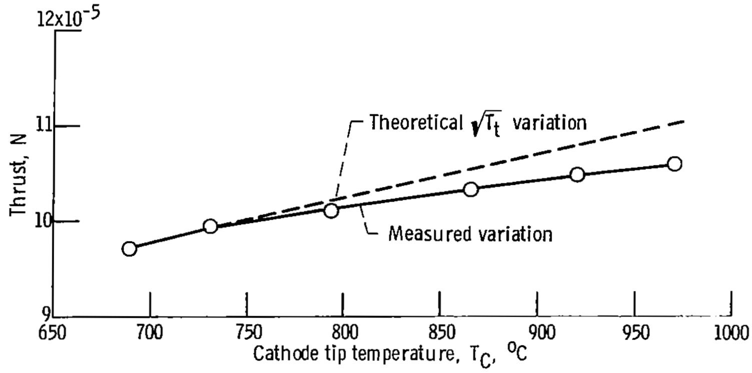


Figure 5. - Cathode thrust as a function of tip temperature without a discharge at a target angle of 10^o.

Figure 5 compares the measured thrust increase as a function of tip temperature with a theoretically expected square-root variation. The coldest tip temperature is used as a common starting point of comparison.

Comparison of Measured Thrust With Theoretical Thrust

The measured force acting on the target may not represent the actual net thrust from the cathode. However, by making certain assumptions involving the manner of emission from the cathode and the reflection characteristics of the target, it is possible to derive corresponding values for the cathode thrust with no electrical discharge.

The emission from the cathode is considered to be directed paraxially. This seems to be a reasonable assumption because the cathode is thought to be operating in the transition flow regime with a cathode orifice length to diameter ratio of 4. It is possible that the reflection distribution from the target is somewhere between a specular distribution and a diffuse distribution. The cathode thrust is calculated for both elastic specular and diffuse reflection (at an assumed target temperature of 300 K) and compared to the theoretical thrust in figure 6.

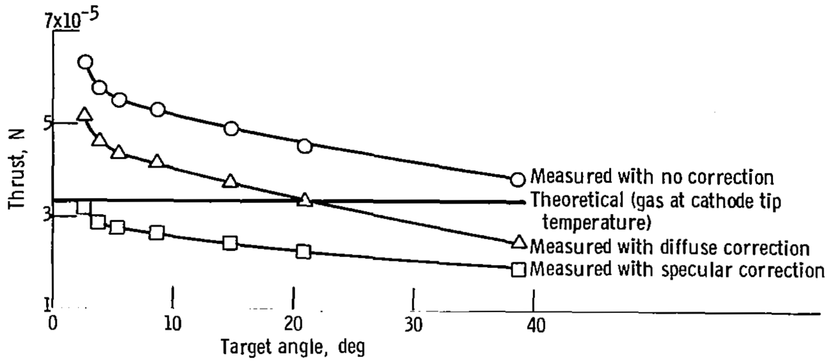


Figure 6. - Comparison of cathode thrust values with no discharge at cathode tip temperature of 1110 K. Correction for diffuse reflection assumes a target temperature of 300 K.

As derived in the APPARATUS AND PROCEDURE section, the thrust of the cathode (neglecting any particle reflections from the target) can be expressed as

$$F = \frac{\pi^2 M L^2 (\theta + \varphi)}{3\tau^2 R \cos \alpha}$$

Because this expression does not account for the measured additional thrust due to molecules bouncing off the target, it could be modified to give a more accurate thrust measurement of the cathode. If elastic specular reflection from the target occurs, then the uncorrected measured cathode thrust is simply twice the measured cathode thrust corrected for specular reflection F_s, or

$$F_s = \frac{F}{2}$$

or

$$F_s = \frac{\pi^2 M L^2(\theta + \varphi)}{6\tau^2 R \cos \alpha}$$

If diffuse reflection from the target is assumed, a different correction must be used. This correction term is the resultant normal force component on the target for a diffuse distribution of reflected atoms. Figure 7 illustrates the cosine distribution of N number of particles where $N_0 \cos \beta$ equals the number of particles per unit solid angle at any angles of reflection, β. Because the resultant force acting on the target is proportional to $\cos \beta$, the resultant thrust can be computed for a cosine distribution by integrating over the total range of reflection. This component may be expressed as a fraction f of the measured thrust due to reflection by dividing by the total number of particles

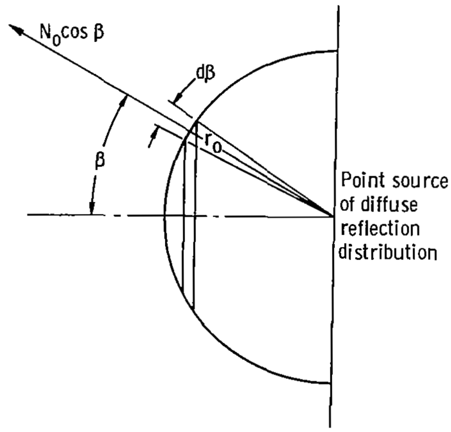


Figure 7. - Integration hemisphere for diffuse distribution of reflected atoms.

$$f = \frac{\int_0^{\pi/2} 2\pi r_0^2 \sin \beta N_0 \cos^2\beta \, d\beta}{\int_0^{\pi/2} 2\pi r_0^2 \sin \beta N_0 \cos \beta \, d\beta}$$

Thus, f = 2/3.

The resulting additional force which acts upon the target is

$$\frac{2}{3} F_T = \frac{2}{3} \dot{m} \sqrt{\frac{8kT_t}{\pi M_o}}$$

This force acts at a distance of

$$r = \frac{R \cos \alpha}{\cos(\theta - \alpha)}$$

from the target axis (see fig. 3(b)). Balancing the torques on the torsion wire yields

$$FR \cos \alpha = F_D R \cos \alpha + \frac{2}{3} \dot{m} r \sqrt{\frac{8kT_t}{\pi M_o}} = K(\theta + \varphi)$$

where F_D is the measured cathode thrust corrected for diffuse target reflection. Thus,

$$F_D = F - \frac{2}{3} \frac{\dot{m} r}{R \cos \alpha} \sqrt{\frac{8kT_t}{\pi M_o}}$$

Substituting for r yields

$$F_D = F - \frac{2\dot{m}}{3 \cos(\theta - \alpha)} \sqrt{\frac{8kT_t}{\pi M_o}}$$

or

$$F_D = \frac{\pi^2 ML^2(\theta + \varphi)}{3\tau^2 R \cos \alpha} - \frac{2\dot{m}}{3 \cos(\theta - \alpha)} \sqrt{\frac{8kT_t}{\pi M_o}}$$

Thus, the diffuse correction term is dependent on the target angle. Figure 6 shows the curves for the theoretical thrust of the cathode, the measured thrust neglecting target reflection, and the measured thrust of the cathode corrected for specular and diffuse reflections, all as functions of target angle. There was no discharge to the keeper. For an equivalent mass flow rate of 47 milliamperes and a cathode tip temperature of 1110 K, the theoretical thrust of the cathode is 3.35×10^{-5} newton. The measured uncorrected and corrected thrust of the cathode are dependent on target angle θ. The sharp decline in thrust with increasing target angle at small angles ($\theta < 10^{\circ}$) indicates that the target increases local pressure. The gradual slope of the curves at larger target angles ($\theta > 10^{\circ}$) suggests that the amount of exhaust beam interception decreases with increasing target angle. This indicates a slight divergence in the emission of the cathode and contradicts the assumption that the emission is not divergent. By considering the emission to be divergent, the measured thrust of the cathode would need further correction. There is probably a small fraction of thrust not measured because of incomplete exhaust beam interception by the target. However, since the slopes of the curves in figure 6 do not indicate a large divergence in the exhaust beam, the simplifying assumption that the emission is not divergent is in good agreement with the actual case for target angles less than 10°, where there may be nearly total interception of the emission by the target.

It should be noted that an electrostatic charge buildup on the insulating target surface would produce a force which would also decrease with target angle θ. A mathematical model of the cathode and target was analyzed to determine the magnitude of this force. For the distances involved and for the maximum electron potentials present the electrostatically produced force was determined to be approximately 1.3×10^{-9} newton. This was well below the sensitivity of the experiment and was, therefore, neglected.

Figure 6 shows that the theoretical cathode thrust value of 3.35×10^{-5} newton is approximately midway between the experimental value corrected for specular target reflection (3.47×10^{-5} N) and the experimental value corrected for diffuse reflection (2.6×10^{-5} N) for a target angle of 10°. The uncorrected measured cathode thrust at 10° is 5.2×10^{-5} newton.

Effect of Mercury Flow Rate

Figure 8 shows the variation of measured force as a function of mercury flow rate for the discharge and no-discharge cases. The data in figure 8 are for a constant target angle of 10° and at a constant tip temperature of 1110 K. Keeper current for the discharge case is 0.5 ampere. The measured force is seen to increase linearly with flow rate for the no-discharge case, as would be expected from the aforementioned relation ($F_T = \dot{m}v$). A slight deviation from linearity in the curve for the discharge case may be explained by noting the change in discharge power. At a given discharge current, the voltage decreased with increasing flow rate, thus decreasing discharge power with increasing flow rate.

The effect of discharge power on the measured force is discussed in the following section.

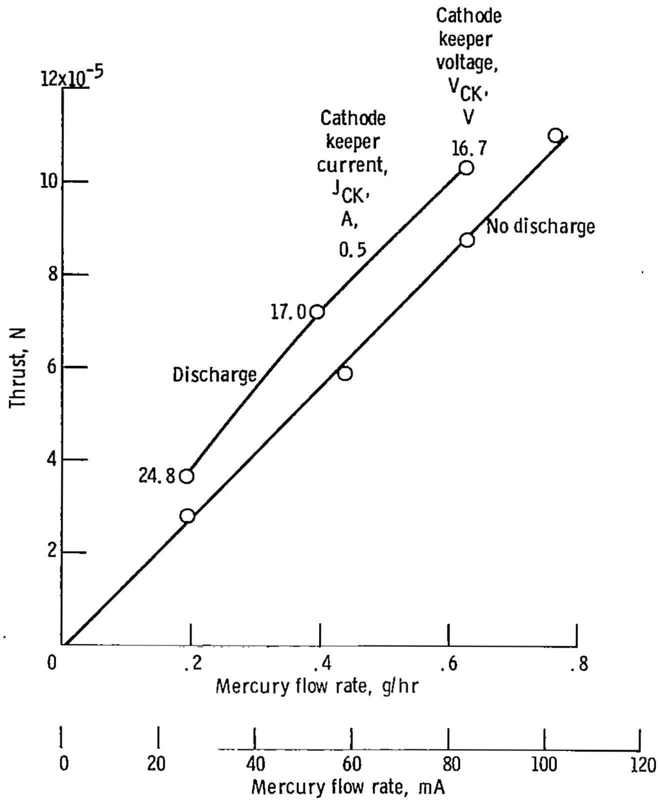


Figure 8. - Measured cathode thrust as a function of flow rate with and without a discharge.

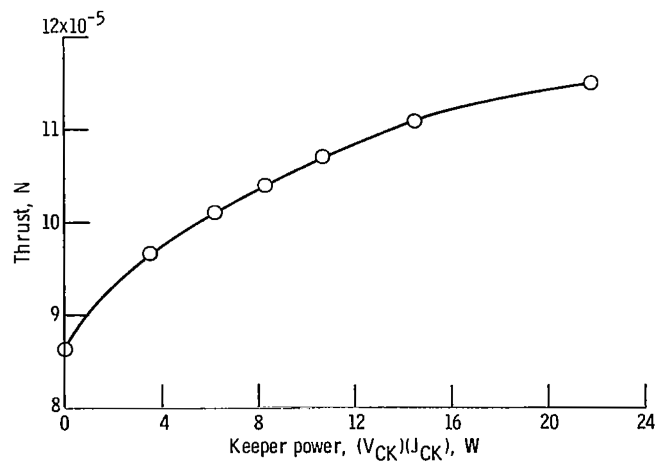


Figure 9. - Measured cathode thrust as a function of keeper discharge power. Cathode tip temperature, T_C, 1110 K; equivalent mass flow rate, 84 mA.

Keeper Power

The measured force is presented as a function of keeper power in figure 9 for values of keeper power up to 22 watts. All data are for a constant target angle of 10°, a tip temperature of 1110 K, and a mass flow rate of 84 milliamperes. Figure 9 shows that the measured force increases at a decreasing rate with increasing keeper power.

It is possible that an increase in keeper power increases the kinetic energy of the gas in the discharge region. This increase in the kinetic energy of the gas could account for the increased thrust measured with a keeper discharge.

Effect of Accelerator on Thrust

With the possibility that ions and/or electrons could be accelerated electrostatically to produce additional thrust, the effect of an accelerator mounted downstream of the keeper was of interest. The effect of accelerator voltage on the measured thrust was investigated with a discharge to the keeper. Figure 10 shows the measured thrust as

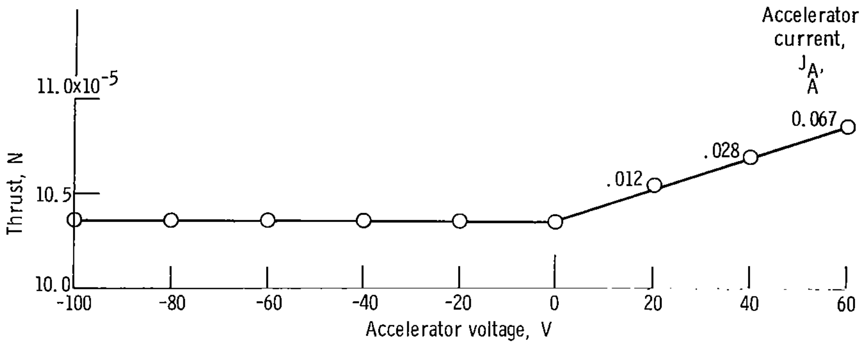


Figure 10. - Measured cathode thrust as a function of accelerator voltage. Cathode tip temperature, T_C, 1110 K; equivalent mass flow rate, 81.6 mA; cathode keeper voltage, V_{CK}, 16.3 V; cathode keeper current, J_{CK}, 0.5 A.

a function of accelerator voltage ranging from -100 volts to +60 volts for a keeper current of 0.50 ampere, a keeper voltage of 16.3 volts, a mass flow rate of 81.6 milliamperes, and a tip temperature of 1110 K. The thrust measured with no accelerator voltage applied was 10.35×10^{-5} newton. There was no measured change in thrust as a negative accelerator potential (up to -100 V) was applied. However, with a positive accelerator potential (up to +60 V) applied, the measured force increased almost linearly, and at +60 V, it was 10.86×10^{-5} newton, which represents an increase of 4.9 percent over the thrust measured with no applied accelerator voltage. These results are consistent with the interpretation that the thrust is the result of expansion of a gas. The positive accelerator voltages resulted in additional discharge power and, therefore, added heating of the gas. The negative accelerator voltages resulted in no additional power (accelerator current was negligible for negative voltages); thus, the gas temperature and thrust were unchanged.

SUMMARY OF RESULTS

The thrust of a hollow cathode using mercury as a propellant was measured with a torsion pendulum having a synthetic mica target. The thrust measurements were taken as functions of target angle, cathode tip temperature, mercury flow rate, keeper discharge power, and accelerator potential.

The measured thrust decreased with target angle and increased with tip temperature, flow rate, keeper discharge power, and accelerator potential.

For a tip temperature of 1110 K, an equivalent neutral flow rate of 47 milliamperes, and a target angle of 10°, the measured thrust was between 2.6×10^{-5} and 5.2×10^{-5} newton for no keeper discharge. These values were in approximate agreement with theoretical values based on the thrust generated from only the neutral gas flow. With the same tip temperature, flow rate, and target angle, but with a keeper discharge of 19 volts and 0.75 ampere, the thrust increased by 28 percent. Additional thrust was obtained when positive accelerator voltages were applied. Typical thrust values obtained were about 0.24 percent of the thrust of the SERT II thruster.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 17, 1971,
113-26.

APPENDIX - SYMBOLS

F measured thrust of cathode, with paraxial emission assumed and neglecting target reflection neglected, N

F_D measured cathode thrust with diffuse correction, N

F_S measured cathode thrust with specular correction, N

F_T theoretical thrust of cathode, N

f correction fraction for diffuse reflection distribution, dimensionless

I moment of inertia of target, $kg\text{-}m^2$

J_A accelerator current, A

J_{CH} cathode tip heater current, A

J_{CK} cathode keeper current, A

J_{CV} cathode vaporizer current, A

K torsion constant of torsion wire, (N)(m)/rad

k Boltzmann constant, 1.38054×10^{-23} J/K

L length of target, m

M mass of target, kg

M_o mass of the mercury atom, kg

$\dot{m}$ mercury mass flow rate, kg/s

N number of particles reflected, dimensionless

N_o number of particles reflected at angle $\beta = 0$, dimensionless

R distance from target axis to cathode tip, m

r distance from target axis to point on target the extended cathode axis intercepts, m

r_o radius of hemisphere for diffuse target reflection integration, m

T temperature, K

T_c cathode tip temperature, K

T_t target temperature, K

V_A accelerator voltage, V

V_{CH} cathode tip heater voltage, V

V_{CK} cathode keeper voltage, V

V_{CV} cathode vaporizer voltage, V

v average speed of mercury atom, m/sec

α angle formed by cathode axis and a perpendicular to the $\theta = 0$ position of the target, rad

β angle of reflection, rad

θ target angle, rad

$\ddot{\theta}$ angular acceleration of target, rad/sec^2

τ period of oscillation, sec

φ angle of rotation of top end of torsion wire, rad

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