Engineering Notes

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Minimum Hole Size in Ion Optics

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Introduction

THE recent emphasis on geocentric missions has led to an increased interest in exhaust velocities in the 10-20 km/s range for electric thrusters.[1] To operate effectively at such exhaust velocities, operation at higher perveance is required. That is, ion optics grids must be spaced closer, and they must have more and smaller holes.

Theory

The current through a single aperture has been found experimentally to be of the form[2]

$$J \propto (q/m)^{1/2} V_t^{3/2} (d_s/\ell_e)^2 \tag{1}$$

where q and m are the charge and mass of the accelerated ions, V_t is the total voltage between the grids, d_s is the screen hole diameter, and ℓ_e is the equivalent acceleration length. The length, ℓ_e, can be expressed as

$$\ell_e = (\ell_g^2 + d_s^{2/4})^{1/2} \tag{2}$$

where ℓ_g is the spacing between the grids. Equation (1) can be rearranged to give

$$(J/V_t^{3/2})(\ell_e/d_s)^2 \propto (q/m)^{1/2} \tag{3}$$

The grouping on the left is called the normalized perveance. $J/V_t^{3/2}$ is simply termed perveance. For a given propellant (a fixed value of q/m), the maximum permissible value for normalized perveance is approximately constant, varying primarily with the ratio of accelerator-to-screen hole diameters, d_a/d_s.

A significant conclusion can be drawn from Eq. (3). That is, for a given propellant and a fixed ion-optics geometry (fixed values of d_a/d_s and ℓ_g/d_s, hence also ℓ_e/d_s), the current through a single hole is independent of either the absolute size of the hole or the grid spacing. To maximize the total beam current for a given propellant and total voltage, then, a large number of small holes should be used in closely spaced grids.

An early experimental study of the effect of hole size[3,4] indicated that the current capacity of a single aperture was not independent of hole size for screen-hole diameters smaller than about 2 mm, but decreased with decreasing hole diameter in this range. This effect was later confirmed in a separate and independent study.[5] Despite the duplication of this hole-size effect, there has been no apparent explanation why absolute size should have any significance.[6]

Submitted July 13, 1983; revision received May 25, 1984.

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It is proposed herein that this apparent effect of absolute size is, instead, due to the relatively greater significance that errors in alignment will have for smaller hole sizes.

The nature of the alignment problem is indicated in Fig. 1. The accelerator hole is displaced relative to the screen hole by an amount δ. To reduce the direct impingement to a negligible level with the displaced accelerator grids, the beamlet would have to be reduced in size to the diameter indicated by the dashed line, which is $d_a - 2\delta$. (This ignores a second-order effect in which the beamlet is bent slightly toward the nearest edge of the accelerator hole, making some further reduction in beamlet size necessary.)

The variation of normalized perveance with relative accelerator-hole diameter, d_a/d_s, has been studied from both computer simulation and experimental viewpoints. The experimental variation of normalized perveance is indicated in Fig. 2. Numerically, a 1% decrease in accelerator-hole diameter typically results in 1.5-2% decrease in perveance. Inasmuch as the effective change in diameter is twice the displacment, δ, the fractional reduction in normalized perveance should be 3-4 times δ/d_a.

Comparison of Theory and Experiment

Two sets of experimental data were considered. One was for 30-cm grids,[3,4] while the other was for much smaller grids in an ion-optics study.[5] Other studies were also considered, but were felt not suitable for the error-analysis approach used here, either because of incomplete data or a different experimental approach.

For example, a study of variable grid spacing also included the effect of hole size.[7] A mechanical, rather than a visual, alignment procedure was used therein. Information on the tolerances involved cannot be estimated from information presented in the paper.

The 30-cm experimental data are presented in Fig. 3. For the visual/manual techniques used, an initial alignment error of about 0.1 mm is estimated. Spring clips were used to hold these grids together. Because these clips were almost certainly of unequal tension, one side would have been expected to hold, while the other side slipped as the result of unequal thermal expansion. The temperature difference is roughly 100°C at operating conditions,[6] while the diameter at which the spring clips were located was about 35 cm, so that a relative slippage of about 0.18 mm would be expected. The total probable displacement should then be $\sim(0.10^2 + 0.18^2)^{1/2} = 0.20$ mm.

The theory curve was normalized to the experimental data point at a d_s of 2.4 mm, where the effect of misalignment

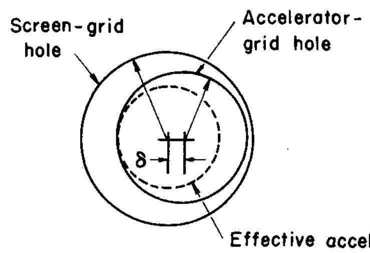

Fig. 1 Axial view of ion-optics holes showing effects of grid displacement, δ.

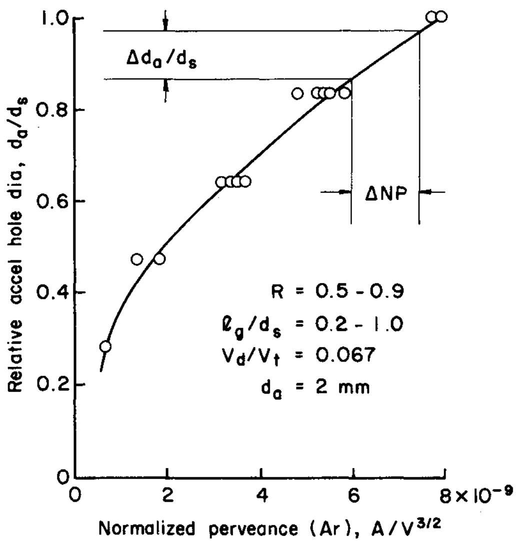

Fig. 2 Effect of accelerator hole diameter on maximum normalized perveance.

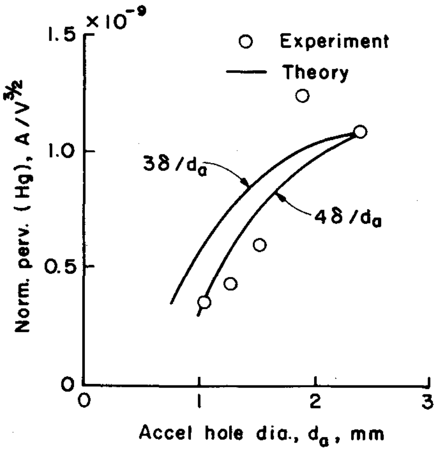

Fig. 3 Comparison of error theory with data from 30-cm thruster (Refs. 7 and 8).

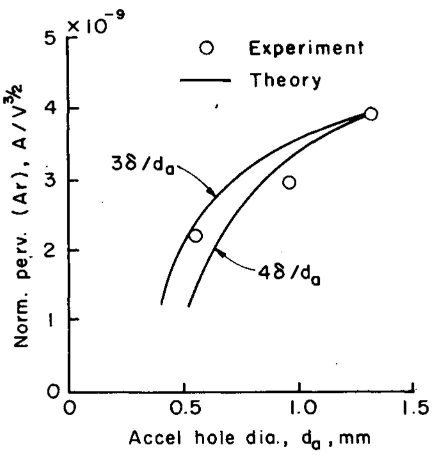

Fig. 4 Comparison of error theory with data ion-optics apparatus (Ref. 9).

should be smallest. Using the assumed accelerator displacement of 0.2 mm and the previously described effect of displacement on normalized perveance, the curves shown were produced. The upper curve was for a perveance change of $3\delta/d_a$, while the lower curve was for $4\delta/d_a$.

A similar approach was used for the data from the more recent ion optics study,[5] which are presented in Fig. 4. The maximum distance between supports in this study was only ~2 cm, so that the displacement due to relative thermal expansion could be ignored. The assumed alignment error was then only the initial value of 0.1 mm. Using this value and normalzing it to the data point for a d_s of 2.4 mm, the theory curves shown were produced.

Conclusions

The general trends of theory and experiment are similar. Because of the statistical nature of the problem, exact agreement should not, of course, be expected.

As stated earlier, there is no theoretical reason why smaller holes should have a decreased normalized perveance. The agreement between experiment and the error analysis presented herein indicates that past adverse effects of small ion-optics holes were due primarily to alignment errors. An obvious implication of this conclusion is that grids with smaller holes must be aligned with greater precision, if the full advantages of the smaller holes are to be realized.

The mounting techniques for the cited studies are, of course, not those used in current thrusters. Unfortunately, the visual/manual techniques used in these studies are still widely used for thrusters. The error associated with looking through a low-power magnifier and moving the grids by hand is therefore still present. A variety of mechanical jigging and alignment techniques will permit higher precision, and should be considered as replacements for what must now be considered an obsolete approach.

References

[1] Kaufman, H.R., and Robinson, R.S., "Electric Thruster Performance for Orbit Raising and Maneuvering," *Journal of Spacecraft and Rockets,* Vol. 21, March-April 1984, pp. 180-186.

[2] Kaufman, H.R., "Technology of Electron-Bombardment Ion Thrusters," in *Asvances in Electronics and Electron Physics,* Vol. 36, L. Marton, ed., Academic Press, New York, 1974, pp. 265-373.

[3] Rawlin, V.K., Banks, B.A., and Byers, D.C., "Dished Accelerator Grids on a 30-cm Ion Thruster," *Journal of Spacecraft and Rockets,* Vol. 10, Jan. 1973, pp. 29-35.

[4] Rawlin, V.K., "Studies of Dished Accelerator Grids for 30-cm Ion Thrusters," AIAA Paper No. 73-1086, Oct. 1973.

[5] Aston, G., Kaufman, H.R., and Wilbur, P.J., "Ion Beam Divergence Characteristics of Two-Grid Accelerator Systems," *AIAA Journal,* Vol. 16, May 1978, pp. 516-524.

[6] Kaufman, H.R., and Robinson, R.S., "Ion Source Design for Industrial Applications," *AIAA Journal,* Vol. 20, June 1982, pp. 745-760.

[7] Rovang, D.C. and Wilbur, P.J., "Ion Extraction Capabilities of Very Closely Spaced Grides," AIAA Paper No. 82-1894, Nov. 1982.

Thermal Control System of the Purdue University Space Shuttle Payload

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A REVIEW of the performance of the thermal control system used on the Purdue University Small Self-Contained Payload (SSCP) flown aboard STS-7 has been completed. During the design of this payload, severe

Received Jan. 13, 1984; revision submitted May 11, 1984.

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