NOTES

Experimental Plasmajet Thrustor Results

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Experimental and analytical development work on thermal arc jet propulsion devices for operation in the general area of 800- to 1200-sec specific impulse is described. The major accomplishment is the development of the hot-wall thrustor design to the point where theoretical frozen flow efficiencies have been equaled or slightly exceeded during several tests. Repeated experimental measurements of 50% efficiency at 1000 sec have been made. Heat transfer and efficiency are analyzed, and extensive experimental data are discussed.

Introduction

THIS paper reports results in the initial development phase of a thermal arc propulsion system. More complete details are given in Refs. 1 and 2. The need for such a system has been shown in many application studies, for example, Refs. 3 and 4, where it is shown that a specific impulse in the range from 1000 to 2000 sec will be optimum for many early missions in space. The development of this thermal arc space propulsion system will require the successful attainment of the following: 1) favorable efficiency and specific impulse, 2) reasonable lifetime with an extremely high level of reliability, and 3) integration of the thrustor into a complete space propulsion system. The work reported here has concentrated on the development of favorable efficiency and specific impulse. Previous investigations[5,6] have shown the desirability and advantages of the hot-wall type of design, and this program concentrated on its development. The energy loss caused by the anode voltage drop and thermal conduction to the wall was reduced since the walls of the thrustor were allowed to reach temperatures on the order of 5000°F. This also provides the hot surfaces that are required if regenerative cooling is to be used. The hot-wall design was expected to improve the radial flow profile, and this expectation has been supported by the test data and observation of the experimental runs.

Experimental Results

Two thin copper cantilever beams support the thrustor and carry the current. Thrust is measured with a strain-gage load cell. The systems that comprise the test stand are described in detail in Ref. 2.
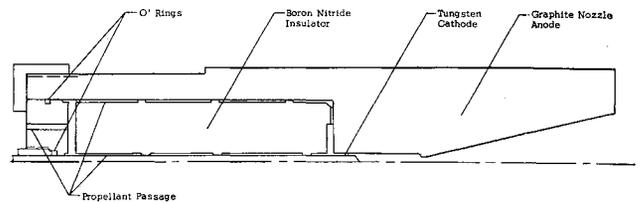
Fig. 1 The H-100-F thrustor

The configuration of Fig. 1 placed the seals far from the hotter portions of the thrustor so that they could be cooled with the propellant. Figure 2 shows the initial results. A complete calibration of the test setup was made after this first run, but the thrustor was not disturbed. At the end of the run, a certain amount of erosion had occurred in the nozzle, and the throat was eroded to approximately 140% of its original diameter. The efficiency obtained on the second run was about 5% lower than that of the first run. This was attributed to a combination of the erosion of the throat plus some deterioration of the O-ring seals from an inadvertant stoppage of propellant flow before the thrustor had sufficient time to cool. The total weight loss to the cathode was 0.023 g/kw-hr, and the total weight loss of the anode was 0.006 g/kw-hr, including an unknown amount of sealing material (water glass) which had been used to impregnate the graphite anode to reduce leakage through its pores. An approximate check of the weight of graphite anode eroded on a volume basis confirmed the forementioned figures. The total running time during these two tests was 60 min. The leakage through the graphite of this thrustor has been measured qualitatively at about 1% with impregnation and 10 to 20% without.[2]

Discussion

In this design, the propellant enters the boron nitride insulator and divides into two concentric annular flow passages, as shown in Fig. 1. The smaller inner passage cools the cathode with about 10% of the flow. A small constant cross-section cathode was used to allow the tip to obtain a uniform temperature and to ease compensation for erosion. This cathode design has worked quite well. The rest of the propellant passes through the outer annular passage, where it cools the front electrode and nozzle. The annular passage was used for simplicity; more refined design would use some arrangement of axial grooves that maximize the ratio of wetted circumference to hydraulic radius.

The propellant passes from this annular passage through a set of four square grooves, which are arranged in the front face of the boron nitride insulator to provide the vorticity that stabilizes and stretches the arc. Then the propellant passes around the cathode, providing some cooling, and enters the arc chamber. The ratio of length to diameter was intended to allow the arc to fill the chamber and strike slightly upstream
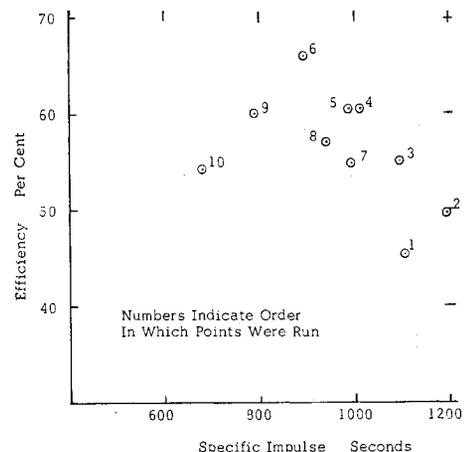

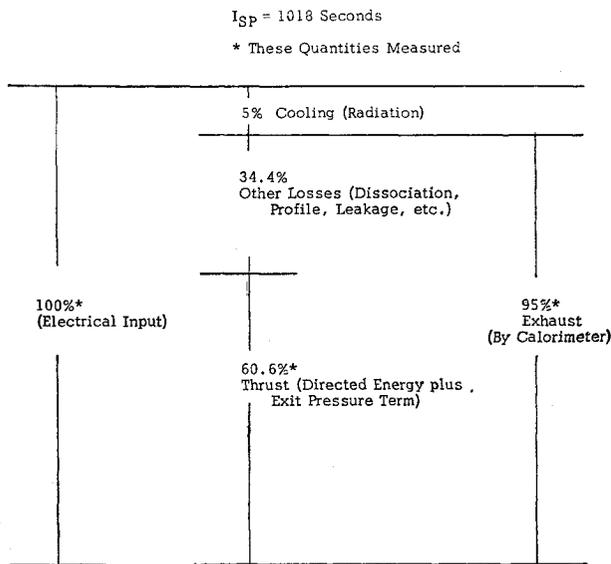**Fig. 2 Test results for H-100-F thrustor**

Fig. 3   Typical H-100-F thrustor energy balance

of the throat. The experimental results indicate that the arc usually did strike in the desired place, and that the given geometry of subsonic arc chamber, immediately followed by a throat and expanding nozzle, did give relatively uniform flow and some recombination.

A typical experimental energy balance for this thrustor is shown in Fig. 3. The value of 60.6% of the electrical input appearing as directed energy is approximately equal to the ideal efficiency for frozen flow. When heat transfer, profile loss, and frictional loss are considered, it appears that some recombination was occurring. It is felt that this is due at least partly to the convergent-divergent geometry used where there is a low-velocity, high-density region that serves to promote recombination and also acts as a "trap" for non-equilibrium electrons. The low cooling loss of approximately 5% indicates that fairly effective regenerative cooling was being achieved (by conduction through the electrode and nozzle), since the electrical anode heating plus conduction should be considerably greater than 5%. The other losses of 34.4% due to dissociation, profile, leakage, etc., appear to be consistent with the assumption of reasonable profiles and a freezing-point pressure of about 1 atm.

Life has not been a prime goal of this effort; however, the results obtained with a tungsten insert in the H-100-F thrustor appear to be promising. This insert has been operated for approximately 4 hr at about 1000 sec with less than 0.1% change in diameter, thus indicating a life of about 30 hr. There is strong evidence that with more direct regenerative cooling this can be increased to 100 to 500 hr at 1000 sec.

Conclusions

1) It is possible to obtain over 50% efficiency at 1000-sec specific impulse using hydrogen in the hot-wall thrustor described. This geometry appears to give a relatively uniform exhaust, good operating stability, and some recovery of dissociation energy. However, considerably more experimental effort will be required before the results will be understood well.

2) Complete regenerative cooling with negligible external energy loss at 1000 sec appears possible with hydrogen as propellant by combining the features of the H-100-C and H-100-F thrustors. The potential efficiency is about 70% at 1000 sec.

References

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Deflections of an Inflated Circular-Cylindrical Cantilever Beam

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Nomenclature

l = beam length, in.
R = cylinder radius, in.
t = wall thickness, in.
A = cross-sectional area, in.^{2}
p = internal pressure, lb/in.^{2}
P = lateral load at tip, lb
q = distributed lateral load
E = Young's modulus, lb/in.^{2}
G = shear modulus, lb/in.^{2}
d_b = tip deflection due to bending, in.
d_s = tip deflection due to shear, in.
σ = stress, lb/in.^{2}
σ_M = maximum stress in axial direction, lb/in.^{2}
σ_0 = minimum stress in axial direction, lb/in.^{2}
y = lateral deflection of beam, in.
x = distance from loaded end, in.
θ, θ_0 = angular positions

I. Introduction

THE use of inflatable structures for applications in space suggests itself because of their low weight and their suitability for light loads. A discussion of such space structures is given by Leonard, Brooks, and McComb.[1] Among the structures they consider is the inflated circular-cylindrical tube acting as a cantilever. They derive an equation for the collapse load of such a beam on the assumption that at failure the root folds like a plastic hinge. On this basis they show that the maximum tip load carried is $P = \pi p R^3/l$, where p is the internal pressure. They obtain test data that are in agreement with this equation. An inflated circular-cylindrical tube carrying a constant moment is considered by Stein and Hedgepeth.[2] They obtain a relationship between beam curvature and moment. Other inflatable structures are discussed by Topping[3] and Harris and Stimler.[4] Buckling