formed on the ion-beam collector (Fig. 15) at the spot where the ion beam impinges.

An interesting observation, which was made accidentally during testing of the laboratory prototype, was that the thruster could be operated, albeit at reduced performance, with no heater current supplied to the cathode filament. It appears that the tungsten filament becomes partially cesiated, and the lowered work function together with the heating provided by radiation from the ionizer is sufficient to produce the required electron emission.

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Effect of Background Pressure on Magnetoplasmadynamic Thruster Operation

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The effect of environmental pressure on magnetoplasmadynamic (MPD) thruster operation was studied. Spectroscopic data indicated no significant effect for pressures below 2×10^{-4} torr. Above this pressure, the effects of collisions between the propellant and background gas were detected; that is, the exit velocity of the primary propellant was reduced. The entrainment and acceleration of background gas was also noticeable above this pressure. Both effects increased in magnitude with increasing tank pressure. It can be seen from the data in at least one case that entrainment seemed to contribute a majority of the thrust at a pressure of 0.2 torr.

Introduction

EFFICIENCIES reported for magnetoplasmadynamic (MPD) thrusters are presently subject to certain reservations.[1] Foremost among these is the expectation that the testing environment, i.e., the presence of background gas, might substantially affect thruster operation. The available data on this subject[2–5] leads to no clear conclusion, and even seems contradictory. In the results of Jones and Walker,[2] the thrust decreased monotonically with increasing tank pressure. In the results of Cann et al.[3,4] there is a minimum in the thrust against tank pressure curves with a net increase in thrust as one goes from very low to very high pressure. The results of Bennett et al.[5] were generally consistent with those of Jones and Walker. In all of these studies the measurements reported were limited to tank pressure, thrust, and thruster operating parameters.

The present study attempts to determine if both types of results described previously are reproducible, and, if so, in what regimes each applies. This study also incorporates beam diagnostics to examine the nature of the thruster-environment interaction. The axial velocities of both the primary propellant and the background gas were measured by a spectroscopic Doppler shift technique.[6]

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Apparatus and Measurement Techniques

All experiments were performed in a 15-ft-diam, 65-ft-long vacuum tank.[7] The work was done with the water-cooled thruster[2,8,9] shown in Fig. 1. The thrust measurements were made using a parallelogram-pendulum thrust stand. The electrical power to the thruster was brought onto the stand through coaxial lines terminated on coaxial mercury pots. The power was supplied by commercial welding power supplies. Deflection of the stand was sensed by a linear differential transformer with output indicated on a strip chart recorder. The system was calibrated by a weight and pulley

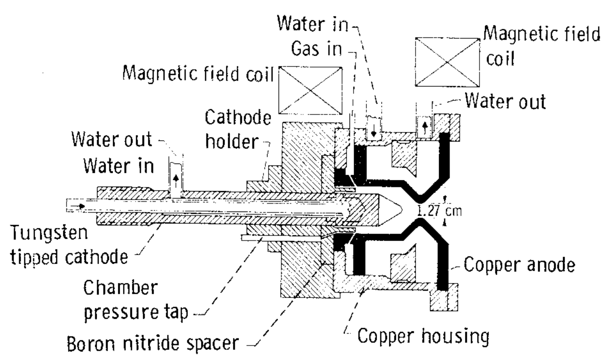

Fig. 1 Schematic of water cooled MPD arc thruster.

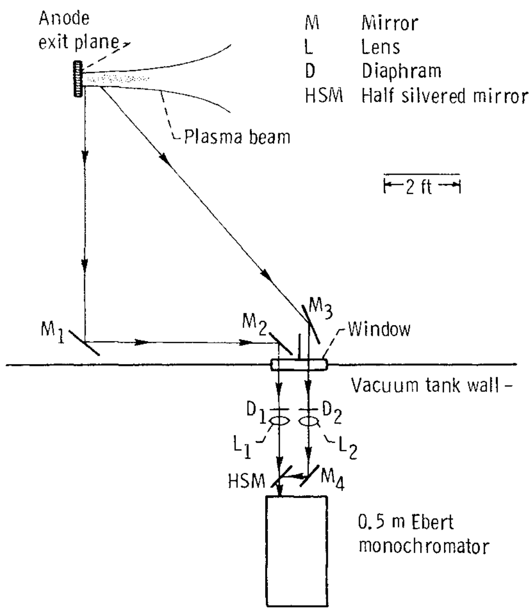

Fig. 2 Optical arrangement.

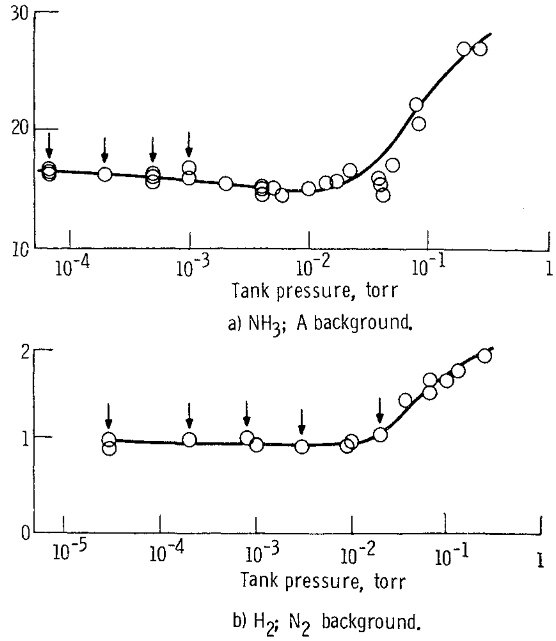

Fig. 4 Thrust power ratio vs tank pressure.

arrangement. A 25-cm-diam steel bucket or "thrust killer" was mounted on a shaft on the thrust stand so that it could be swung down in front of the thruster and thereby remove the directed energy of the beam. The thrust was measured by blocking the exhaust beam momentarily with the thrust killer and observing the change in thrust stand deflection. To check this technique the stand deflection resulting from turning off the arc current was measured at a number of operating points. This value was corrected for current tare (obtained by shorting anode to cathode) and cold flow tare. Comparison of these results with the corresponding thrust killer measurement produced agreement within 5%. Gaseous propellant flow rates were measured by the use of small jeweled sonic orifices calibrated for flow rate against upstream pressure.

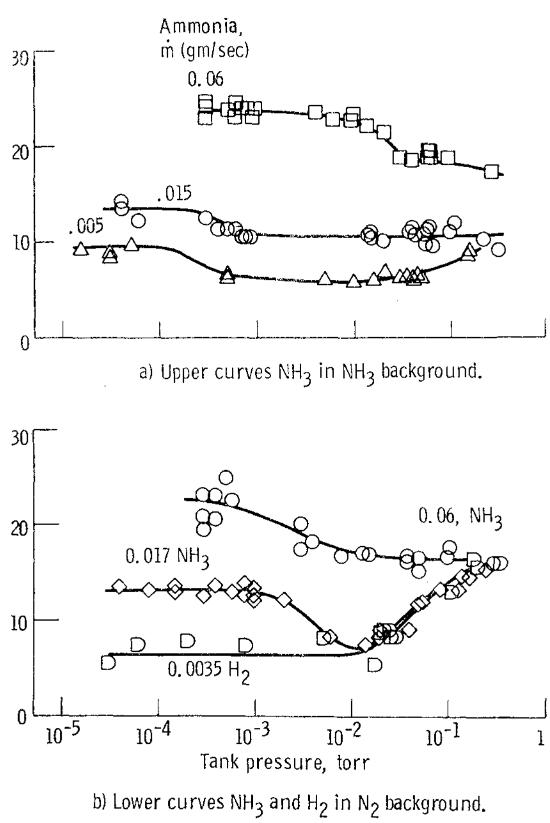

Fig. 3 Thrust power ratio vs tank pressure.

The tank pressure was measured by a Bayard-Alpert type ionization gage at pressures below 10^{-3} torr. Above this pressure a thermocouple gage was used. Both gages were calibrated on air and a correction factor is conventionally applied for other gases. In many experiments the tank contained a mixture of two or more gases in unknown ratios. For this reason correction factors were not applied to the gage readings. Pressures quoted should therefore be considered accurate to within approximately a factor of three.

The axial velocities were obtained by measuring the Doppler shifts of the various spectral lines emitted by the plasma constituents (Fig. 2). The small Doppler shifts were measured by a chopping technique.[6] The expected uncertainty in velocity is about 1 km/sec.

Procedure

The thrust was measured as a function of tank pressure while holding arc power and mass flow rate approximately constant. Tank pressure was varied in one of two ways. In the first method the thruster was started at an intermediate tank pressure and data were taken while the tank pressure was reduced. In the second method a controlled flow of inert gas, different than the propellant, was bled into the tank. The first method of varying tank pressure more nearly simulated the experiments of others. The second method had two important advantages: 1) the tank pressure could be set and maintained indefinitely at any value in the range of interest, and 2) the propellant and background particles could be discriminated spectroscopically. One could therefore study the behavior of the beam gas and background gas independently.

Variation of Thrust/Power Ratio with Tank Pressure

The results obtained are shown in Figs. 3–7. In Fig. 3a, the thrust/power ratio (T/P) is plotted against tank pressure for ammonia propellant at three different mass flow rates. At

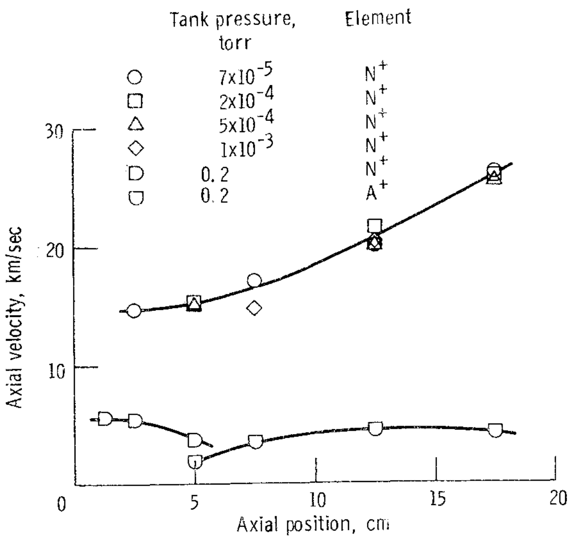

Fig. 5 Axial velocity vs axial position for singly ionized nitrogen atom. NH_3 propellant, A background.

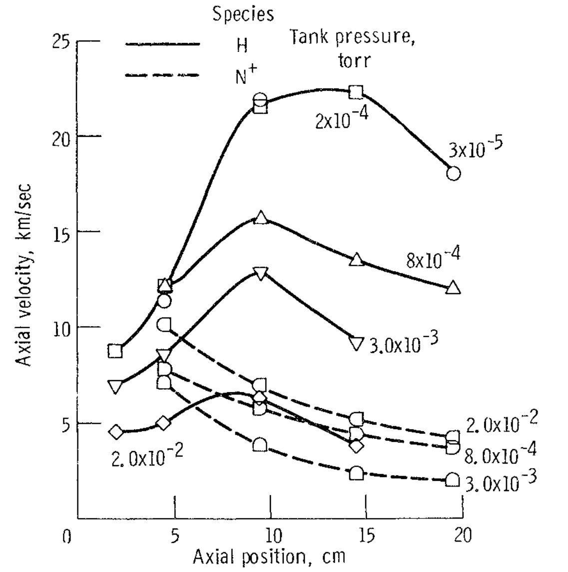

Fig. 6 Axial velocity vs axial position. H_2 propellant, N_2 background.

the highest mass flow rate ($\dot{m}$ = 0.06 g/sec) T/P decreased monotonically with increasing tank pressure in agreement with the results of Jones and Walker. At the lowest $\dot{m}$, T/P at first decreased then increased with increasing tank pressure. In general, however, T/P had its maximum value at minimum tank pressure. This is in qualitative agreement with the results of Jones and Walker.

For the data of Fig. 3a, the tank pressure was varied by varying the pumping capacity while operating the thruster. Thus the background was the same gas as the propellant. The results of Jones and Walker were obtained either by varying the pumping capacity or by bleeding H_2 into the tank while operating on H_2. Again the background gas was the same as the propellant.

For the data shown in Fig. 3b, the tank pressure was varied by bleeding N_2 into the tank while operating on NH_3 or H_2. At high mass flow rate, the T/P ratio fell off monotonically with increasing tank pressure. At intermediate mass flow rate there was a pronounced minimum in the curve at a pressure of about 10^{-2} torr. This case was quite similar to the general behavior of Cann's data,[3,4] the minimum even occurred at about the same pressure. Finally, at a very low mass flow rate, there was a steep rise in the T/P ratio as the pressure was increased above about 10^{-2} torr.

In all of Cann's data, as in the data of Fig. 3b, the tank pressure was varied by bleeding a gas, other than the propellant, into the vacuum tank. This method was common to all of the cases in which a pronounced minimum occurred in the curve of T/P ratio against tank pressure, or in which the maximum thrust occurred at pressures other than the minimum.

Interest in the effect of environmental pressure stems primarily from the limitations of most available vacuum facilities. Those who are limited to making measurements on a thruster operating in the 10^{-1} torr pressure range desire some basis for estimating the effect of background gas on their results. For this purpose the results of Fig. 3b are not very useful since the background gas was different than the propellant. Instead, one should rely on the relationships shown by Fig. 3a. However, these relationships change with mass flow rate and we know of no method for deciding what constitutes a low or high mass flow rate for a thruster that has not been tested over a wide range of pressure. Consequently, no general conclusion can be drawn as to what correction should be made for experiments performed at high background pressures.

Correlation of Thrust/Power Ratio and Doppler Shift Measurements

Figure 4 is a plot of T/P ratio against tank pressure for two particular conditions. For Fig. 4a, the arc power was 25 kw and the $\dot{m}$ was 0.020 g/sec of NH_3. The background pressure was varied by bleeding argon gas into the tank. For Fig. 4b, the arc power was about 20 kw. The $\dot{m}$ was 0.0035 g/sec of H_2. The pressure was varied by bleeding N_2 into the tank. In both cases the thrust was fairly constant up to about 10^{-2} torr above which it rose rapidly.

The spectroscopic data corresponding to Fig. 4a is shown in Fig. 5. The average axial velocity of the singly ionized nitrogen (4630.6 Å) in the thruster exhaust was measured at a number of axial positions. For the four tank pressures indicated by arrows on Fig. 4a (0.07, 0.2, 0.5, 1.0 $\times 10^{-3}$ torr) the axial velocity is plotted against axial position in Fig. 5.

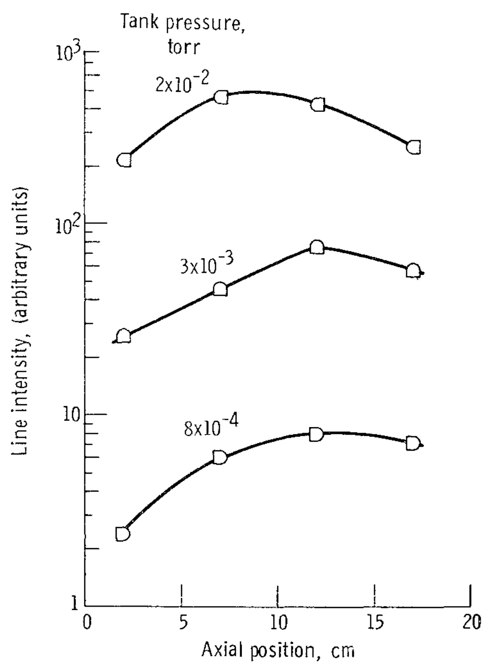

Fig. 7 Nitrogen ion line intensity vs axial position. H_2 propellant N_2 background.

Figure 5 shows that, for these pressures the velocities were the same. That is, up to a pressure of 10^{-3} torr, the velocity of the ions in the thruster exhaust is insensitive to the presence of the argon. In addition, at each of the aforementioned pressures, the argon spectrum lines were not intense enough to be separated from the weak background spectra of molecular hydrogen and nitrogen. That is, the argon spectrum lines were about 2 orders of magnitude lower in intensity than the N^+, N^{++}, and H lines. Thus, for this case, at pressures up to 10^{-3} torr on interaction between the thruster exhaust and the background gas was detected.

At higher tank pressures ($>10^{-2}$ torr) the N^+ velocity began to decrease and argon lines became intense enough to be positively identified. Figure 5 also includes data obtained at 0.2 torr tank pressure. At this pressure the N^+ velocity was greatly reduced. In addition the A^+ spectrum line at 4589.9 A was quite intense and exhibited a definite Doppler shift. Both the velocity and intensity of the A^+ were comparable to those of the N^+ line.

The information contained in Fig. 5 can be summarized by the following statements: 1) the argon background gas had no significant effect on thruster operation at pressures below 10^{-3} torr; 2) at higher pressures the argon background gas reduced the exit velocity of the primary propellant; 3) also, at higher background pressures the argon was entrained and accelerated by the thruster.

Additional conclusions can be drawn from Figs. 6 and 7 which give the spectroscopic data corresponding to Fig. 4b. Hydrogen atom axial velocities are plotted in Fig. 6 for the 5 pressures indicated by the arrows in Fig. 4b. Note from Fig. 4b that the thrust was about the same at all five pressures. At the lowest two pressures (0.3 and 2.0×10^{-4} torr) the H velocities reached the same maximum. The N^+ background line was not observed at these pressures.

At 8×10^{-4} torr the H axial velocity decreased as shown. Also, at this pressure the N^+ line appeared with a significant Doppler shift. With each succeeding increase in pressure there was a substantial drop in the axial velocity of the propellant H atoms. The velocity of the background N^+ ion did not change a large amount with increasing pressure. However, the intensity of the N^+ line, which should roughly indicate the amount of nitrogen entrained into the beam, increased rapidly with increasing tank pressure. This intensity change is shown in Fig. 7. In this case both the velocity of the primary propellant and the entrainment of background gas are seen to have a monotonic dependence on background pressure. The hydrogen propellant velocity decreased and the amount of nitrogen background gas entrained increased with increasing tank pressure. Both effects showed up spectroscopically at pressures lower than that required for a change in thrust to be detected. This suggests that the dependence of thrust on tank pressure is not always a sensitive indicator of the influence of background gas on thrustor operation.

From the data, it is clear that the presence of background gas effects thrustor operation in two ways. The exit velocity of the primary propellant is reduced and the background gas is entrained and accelerated. The first effect should decrease the measured thrust while the second should increase it.

In the cases we have studied both effects appeared at about the same pressure (5×10^{-4} torr in one case and 5×10^{-3} torr in the other). Both effects increased in importance with increasing tank pressure. The variation of thrust with tank pressure is an indication of their relative effect on overall thruster performance.

In the pressure range above 0.1 torr, the dominant contribution to thrust probably comes from entrained flow. In the case illustrated in Figs. 4a and 5, the thrust doubled as the background pressure was increased from 6×10^{-5} to 0.2 torr. At the same time the axial velocity of propellant species N^+ decreased by a factor of 4 or 5. Consequently, it seems obvious in this case that a majority of the measured thrust at 0.2 torr is due to the entrainment of background gas.‡

It should be restated that the data in Figs. 4–7 were obtained with a background gas different than the primary propellant. This, as was established earlier, tends to exaggerate the dependence of thrust on background pressure. It is also possible that Doppler studies made in this case may exaggerate the magnitude of beam-background interactions relative to those expected with the same propellant and background gas. Additional experiments would be required to determine the degree to which this is the case.

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‡ There is an interesting figure showing entrainment dominated MPD flow at 1 torr ambient pressure in Ref. 10.