Test-Cell Pressure Effects on the Performance of Resistojets

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The effect of test-cell pressure on the performance of two resistojets was investigated. Tests were conducted in a vacuum facility at pressures ranging from 4.3×10^{-5} to 5.4×10^{-1} Torr for two resistojet configurations: a laboratory model and an engineering model for the Space Station. The tests showed that for each thruster there was a decline in performance, even after correcting for test-cell pressure, when tested in vacuum pressures above 10^{-3} Torr. Measurements were made of surface temperature, thrust, and exit-plane pitot pressure over the range of test-cell pressures. From these measurements, the decline in performance of the laboratory-model resistojet at higher cell pressures was attributed to heat losses as a result of convection. For the engineering-model resistojet, the decline in performance was found to be a combination of heat loss and an effect of cell pressure on the nozzle flow.

Introduction

DESIGN and development of a satellite thruster often entails testing in a vacuum facility to simulate space conditions. The vacuum that a facility can provide depends on the type and size of the pumping system available and on the propellant type and flow rate through the thruster being tested. Hence, thrusters can be tested in facilities that vary substantially in vacuum level, or the vacuum in a particular facility can vary considerably depending on the thruster being tested. The purpose of the present study was to determine if the level of vacuum, even after correcting for test-cell pressure, has an effect on the measured performance of a thruster. In this study, two resistojets of different designs were tested in a facility where the vacuum pressure was purposefully varied.[1] Preliminary test results from one of the resistojets have been previously reported.[2]

The upper limit of test-facility pressure, above which thruster performance is adversely affected, has been commented on by several authors. For example, Pisciotta and Eusanio[3] reported that a cell pressure below 10^{-2} Torr (1 Torr = 1 mm Hg) was sufficient for accurately simulating space operating conditions. In another study, Page et al.[4] stated that 10^{-4} Torr was the maximum cell pressure permissible to obtain performance indicative of space conditions. While conducting thrust measurements over a range of cell pressures, other investigators also have reported an increase in thrust with decreasing test-cell pressure.[5-12] This phenomenon has been referred to as the back-pressure effect. A variety of reasons have been offered as to the cause of this effect.

In Refs. 5-7, the effect was attributed to the cell pressure propagating upstream through the subsonic portion of the flow in the nozzle. This explanation was based on test data from a 45-mN resistojet thruster run with hydrogen and ammonia propellants. The throat Reynolds numbers for these tests were about 400 and 800, respectively, for H_2 and NH_3. At these low Reynolds numbers, the flow had a substantial viscous region in the vicinity of the nozzle walls. At higher cell pressures, this viscous region was thought to thicken, thereby inhibiting the effective nozzle expansion process and reducing the exit velocity. For a range of pressures from 3.4×10^{-4} to 5×10^{-1} Torr, a 19% decrease in corrected thrust was reported for the tests with hydrogen and 17% for the tests with ammonia. Their data indicated that to obtain true space performance, a cell pressure of no more than 10^{-1} Torr is required. Donovan et al.[8,9] and Mirtich[13] also attributed the decline in thrust at higher cell pressures to the effect of cell pressure on the flow.

Experimental data of Rothe[14] and Bailey et al.[15] also support this conclusion. Rothe studied the underexpanded flow of unheated nitrogen through two different nozzles of resistojet size using an electron-beam technique. He verified experimentally that there is a substantial viscous region in nozzle flow at a low Reynolds number and demonstrated the effect of cell pressure on the onset of shocks in the flow. Bailey measured the radial pitot pressure in the exit plane of a nozzle as a function of chamber background pressure. While maintaining constant reservoir conditions, a small but consistent increase in the diameter of the isentropic core flow was noted as the cell pressure was decreased. Bailey's data also support the concept that there is an interaction of the ambient gas with the nozzle flow at higher cell pressures.

The effect of cell pressure on nozzle thrust was specifically examined by Sovey et al.[16] Their tests consisted of measuring thrust from the flow of an unheated gas through several nozzles at various Reynolds numbers over a range of cell pressures from 3×10^{-4} to 1 Torr. The propellants were nitrogen and hydrogen, and the throat Reynolds numbers covered a range from 2,200 to 12,000. Sovey et al.[16] found that the thrust measurements, corrected for the ambient pressure force on the nozzle exit area, were constant with varying cell pressure to the point where the cell pressure induced shocks in the flow. This behavior indicated that the cell pressure had no discernible effect on the flow. In a similar sort of investigation, Cooper et al.[17] tested high-area-ratio rocket nozzles with nitrogen and carbon dioxide at throat Reynolds numbers near 12,000. They calculated that there was no effect of the back pressure on the nozzle flow.

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The conclusion that the back-pressure effect is not a novel phenomenon is supported by two other investigators. Kanning[10] reported a decline in thrust for flow in an orifice as well as a nozzle at cell pressures above 10^{-3} Torr. Bird,[18] through his analytical work, demonstrated that the sonic line in the viscous layer intersects the lip of the nozzle, effectively insulating the flow from the external pressure.[19]

An alternate explanation for the back-pressure effect has been proposed by others. McKevitt,[11] for example, concluded that the observed decline in thrust was a result of increased overall heat loss from the thruster brought about by increased gas densities at the higher cell pressures. This conclusion was based on about 40 temperature measurements taken on the augmented catalytic thruster (ACT) at various operating conditions and test-cell pressures. Similarly, Kallis et al.[12] concluded that convective heat loss from the surface of a thruster may not be negligible at higher cell pressures. This conclusion was based on thermocouple readings taken on a 45-mN resistojet operating on various biowaste-derived propellants.

Both McKevitt and Kallis et al. have suggested that as test-cell pressure rises above a certain value, the density of the ambient gas becomes high enough for convective heat transfer, which results in higher heat loss from the thruster. Page et al.[20] specifically considered the heat-transfer effect on the operation of a radiative heater in a resistojet of their design. They concluded that a test-cell pressure of 10^{-2} Torr was the upper limit for tests to simulate accurately space performance.

In summary, the reported back-pressure effect in resistojet testing has been attributed either to the cell pressure affecting the nozzle flow or to increased heat loss as a result of higher gas densities in the test chamber. This paper describes a study that was done to further investigate the effect and to determine whether it is due to momentum effects, a combination of momentum and heat transfer effects, or is purely the result of increased heat loss.

Apparatus and Procedure

The tests were conducted in a vacuum facility measuring 4.6 mm in diameter by 19 m in length. The pumping system consists of 20 oil-diffusion pumps, with four lobe-type blowers in parallel, and four rotating-piston roughing pumps. A complete description of the facility can be found in Ref. 21. The tank pressure was regulated by means of a controlled bleed of nitrogen and by changing the pumping configuration.

Two different resistojets were tested. The first, shown in Fig. 1, was a laboratory-model thruster originally designed to test material compatibilities. It is made of a molybdenum-rhenium alloy and has a radiatively heated heat exchanger shielded with layers of tantalum foil. The thruster has a conical nozzle with a throat diameter of 0.086 cm (0.034 in.) and an area ratio of 101.[1,2]

The second resistojet was an engineering model of the multipropellant thruster being developed for the Space Station. In this thruster, shown in Fig. 2, the propellant is heated in a multichannel heat exchanger, which is conductively and radiatively heated by a platinum sheathed heater. The heat exchanger and nozzle are made of platinum. The nozzle, which has a throat diameter of 0.102 cm (0.040 in.), consists of a conical section appended with a trumpet-shaped section. The conical section has a 10-deg half-angle from the throat to a diameter of 1.542 cm (0.60 in.), giving an area ratio of 225. The trumpet section has a diameter of 5.07 cm (1.998 in.) at

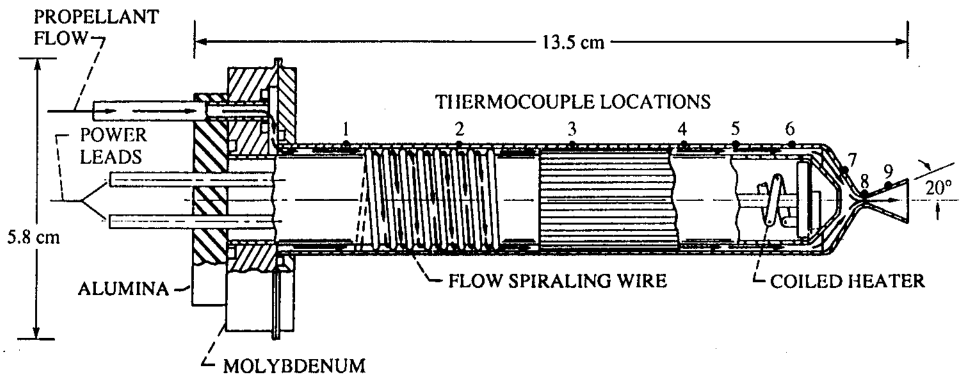

Fig. 1 Laboratory model resistojet thruster.

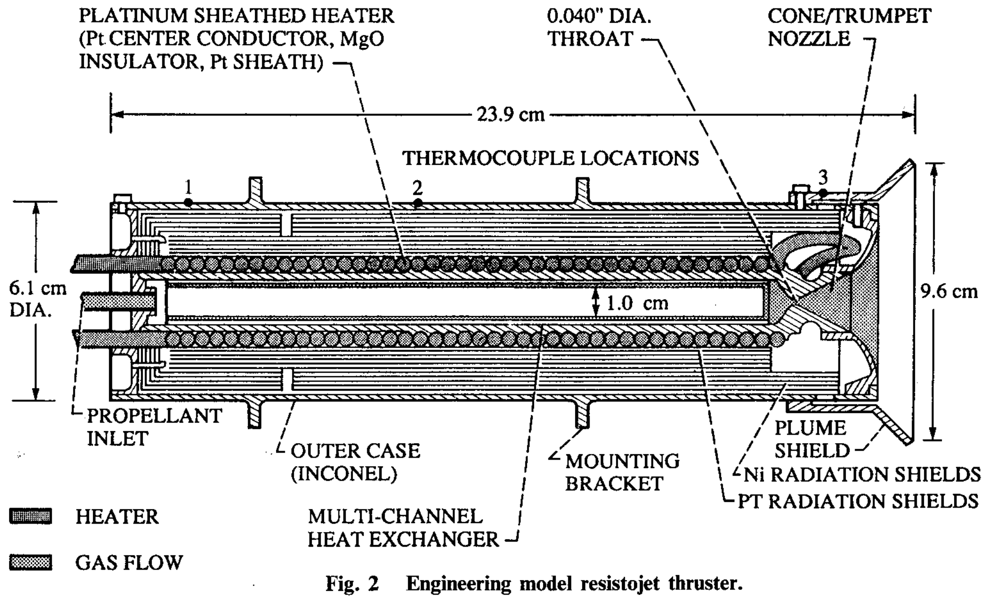

Fig. 2 Engineering model resistojet thruster.

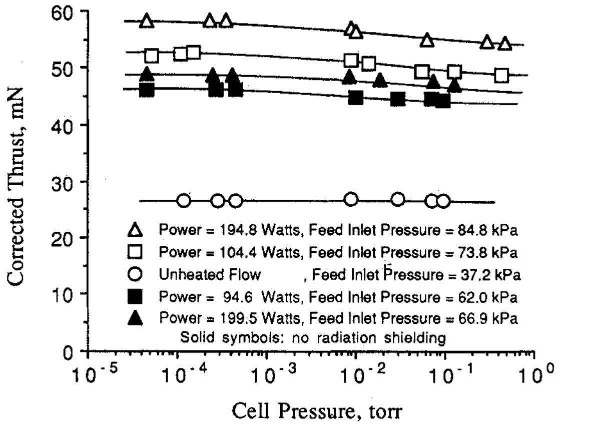

Fig. 3 Corrected thrust vs cell pressure, mass flow rate = 0.0383 g/s, laboratory-model thruster.

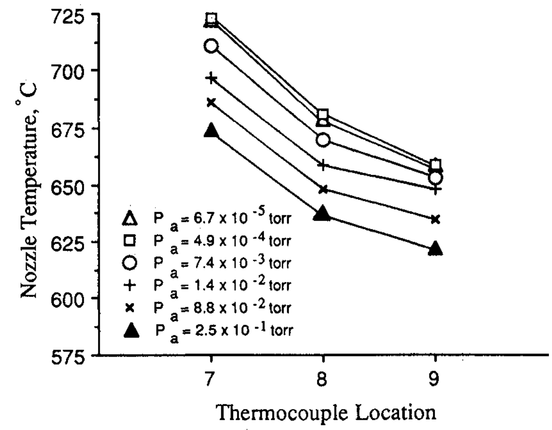

Fig. 5 Nozzle temperature vs location for heated flow, mass flow rate = 0.0383 g/s, power = 99.1 W, laboratory-model thruster.

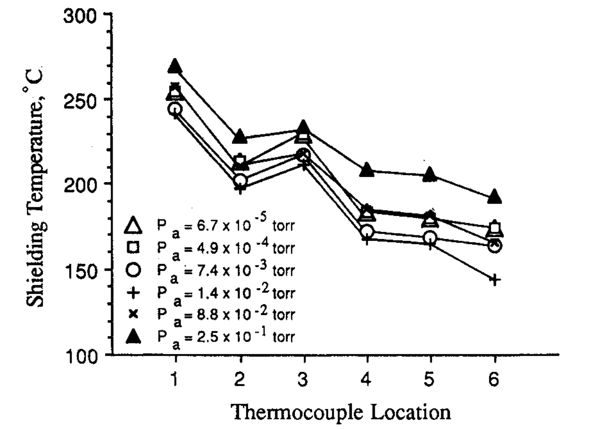

Fig. 4 Surface temperature vs location for heated flow, mass flow rate = 0.0383 g/s, power = 99.1 W, laboratory-model thruster.

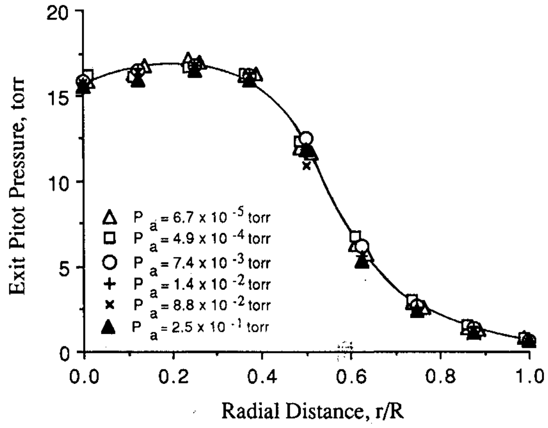

Fig. 6 Exit pitot pressure vs dimensionless radial distance, mass flow rate = 0.0383 g/s, power = 99.1 W, laboratory-model thruster.

the exit for an overall area ratio of 2495. This thruster has internal radiation shielding made of both platinum and nickel. A detailed description of the thruster is available in Ref. 22.

A test run consisted of maintaining both propellant flow rate and power constant, while varying the cell pressure. The propellant in all instances was nitrogen. After steady-state conditions were reached at a particular cell pressure, measurements of thrust, mass flow rate, cell pressure, thruster surface temperatures, heater voltage, heater current, propellant inlet pressure, propellant inlet temperature, and nozzle exit-plane pressure were taken. A complete description of the apparatus and procedure can be found in Ref. 1.

Experimental Results

Laboratory-Model Resistojet

The laboratory-model thruster was operated at mass flow rates of 0.0383, 0.0575, and 0.0767 g/s of nitrogen for both heated and unheated flows. No thrust data were taken at the intermediate mass flow rate of 0.0575 g/s. The throat Reynolds numbers ranged from 1,400 to 10,600. In all cases, the cell pressure was sufficiently low so that the nozzle flow was underexpanded.

The thrust, corrected for the ambient pressure force on the exit area, is presented in Fig. 3 as a function of facility pressure for a flow rate of 0.0383 g/s. In this figure, the corrected thrust for the unheated flow was virtually constant with less than 1% variation. By comparison, the heated flow shows a noticeable decline in corrected thrust at higher cell pressures. The largest percentage drop in corrected thrust was 7.3% and occurred at a power input of 104.4 W and a propellant feed inlet pressure of 73.8 kPa. The performance of the laboratory-model thruster at a flow rate of 0.0767 g/s was similar.

Temperatures of the outer surface of the radiation shielding are presented in Fig. 4 for the operating condition of 0.0383 g/s and a power input of 99.1 W. The thermocouple locations are shown in Fig. 1, and equal axial lengths of 1) 0.5 cm, 2) 3.5 cm, 3) 5.5 cm, 4) 7.5 cm, 5) 8.5 cm, and 6) 9.5 cm measured from the resistojet base, respectively. There was a substantial temperature gradient along the length of the shielding, but there was no variation in temperature with cell pressure at the high-vacuum range of pressures. As the cell pressure was raised, the surface temperature at each location decreased 10–20°C from the temperatures measured at the same locations under hard vacuum conditions. This trend continued to a cell pressure of about 10^{-2} Torr, where the surface temperatures began to increase with rising cell pressure. At a cell pressure of 2.5×10^{-1} Torr, the highest cell pressure set during this run, the surface temperatures were higher than the values at hard vacuum. This general trend was also observed while running the thruster at the other two operating conditions. The lowest temperatures were measured at cell pressures between 10^{-3} and 10^{-2} Torr, and the highest temperatures were measured at the highest cell pressures.

The temperatures on the nozzle surface for the run at a flow rate of 0.0383 g/s and a power input of 99.1 W are plotted in Fig. 5. The relationship between the thermocouple locations and the axial lengths measured from the resistojet base are 7) 10.6 cm, 8) 10.9 cm, and 9) 11.3 cm, respectively. These measurements show there was a substantial temperature gradient along the nozzle at all cell pressures. The temperature at location 7 was the highest and at location 9 the lowest. Unlike the temperatures measured on the radiation shielding, the nozzle temperatures dropped continually by as much as 50°C as the cell pressure was increased above hard vacuum. The thermal behavior of the nozzle for the other two operating conditions was similar.

Pitot pressure measurements in the exit plane of the laboratory-model thruster at six different cell pressures are presented in Fig. 6 for a power input of 99.1 W and a mass flow of 0.0383 g/s. As can be seen, the pressure profile was unaffected by cell pressure. The maximum pitot pressure for this run was 16.8 Torr at a dimensionless radial distance of 0.25 from the centerline. At the centerline, pitot pressure was 15.8 Torr, and at the outer edge of the exit plane, 0.6 Torr. While the magnitude of the pressure in the exit plane for other operating conditions differed, all profiles were found to be similar.

Engineering-Model Resistojet

The engineering-model resistojet was tested at a mass flow rate of 0.0959 g/s. The Reynolds numbers ranged from 400 to 7800 depending on the power input. The measured and corrected thrust are shown in Fig. 7. In this case, there is a decrease in measured thrust for both the heated and unheated flows.

The surface temperatures from a heated flow run of this thruster are shown in Fig. 8. The relationship between the thermocouple locations, illustrated in Fig. 2, and the axial lengths measured from the resistojet base are 1) 2.3 cm, 2) 9.1 cm, and 3) 21.2 cm, respectively. The thermal behavior at locations 1 and 2 was similar to that measured on the radiation shielding of the laboratory-model thruster. The temperature at these two locations initially decreased then began to increase with increasing cell pressure. By contrast, the thermal behavior at location 3 was similar to that measured on the nozzle of the laboratory-model thruster. The temperature dropped continually with increasing cell pressure. The trend was the same for the other heated flow run.

The pitot pressures in the exit plane are shown in Fig. 9 for a flow rate of 0.0959 g/s and a power input of 94.8 W. The measured pressures in the outer two-thirds of the nozzle exit plane follow the cell pressure. The pitot profiles in the center portion of the flow were relatively constant with cell pressure except at the highest cell pressure. At a cell pressure of 4.8×10^{-1} Torr, there was a pressure spike at a dimensionless radial distance of 0.20 from the centerline. The pitot pressures for a heated flow at 228 W of power input are presented in Fig. 10. The profiles are similar to those shown in Fig. 9. The pressures in the outer portion of the nozzle follow the cell pressure, and, in the inner portion of the flow, the profiles were unaffected by cell pressure until the cell pressure reached 4×10^{-1} Torr.

Discussion of Results

Laboratory-Model Resistojet

The experimental data from the laboratory-model resistojet indicate that performance was unaffected at cell pressures as high as 10^{-1} Torr for unheated flows. An effect of test-cell pressure on the performance was found to occur in heated flows at pressures above 10^{-3} Torr. The effect was attributed to increased heat loss from the thruster brought about by convective heat transfer.

The thrust data and exit-plane pitot pressure measurements for unheated flow with the laboratory-model resistojet indicate that there was no effect of cell pressure on the nozzle flow

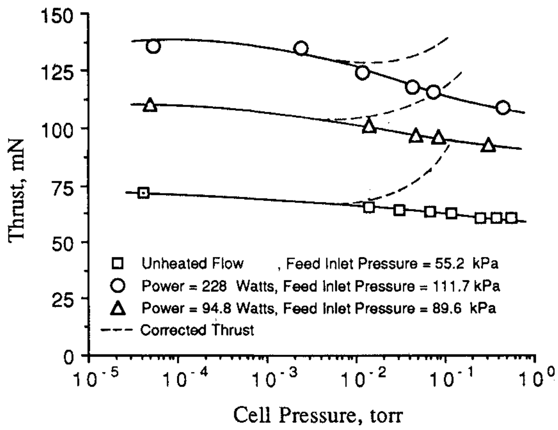

Fig. 7 Thrust vs cell pressure, mass flow rate = 0.0959 g/s, engineering-model thruster.

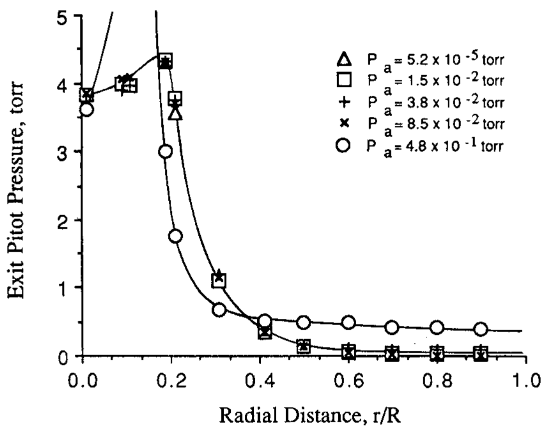

Fig. 9 Exit pitot pressure vs dimensionless radial distance, mass flow rate = 0.0959 g/s, power = 94.8 W, engineering-model thruster.

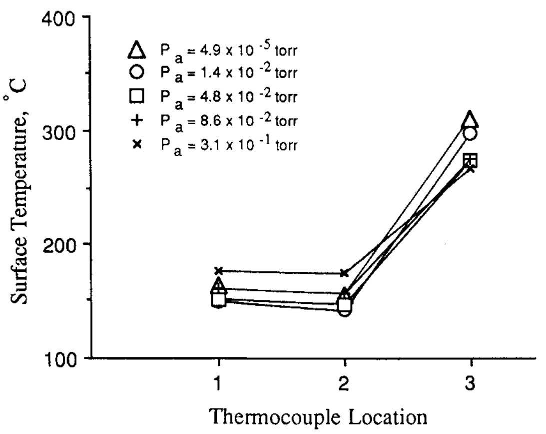

Fig. 8 Surface temperature vs location for heated flow, mass flow rate = 0.0959 g/s, power = 94.8 W, engineering-model thruster.

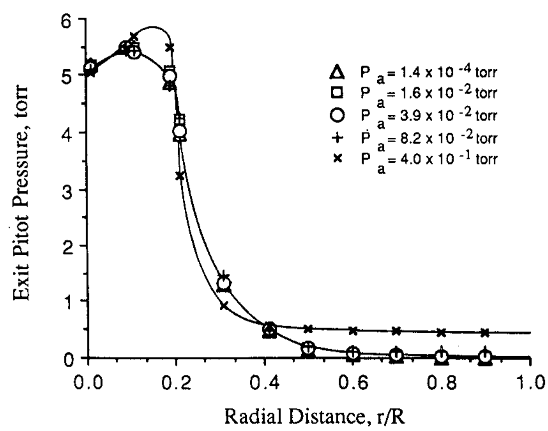

Fig. 10 Exit pitot pressure vs dimensionless radial distance, mass flow rate = 0.0959 g/s, power = 228 W, engineering-model thruster.

as long as the flow was underexpanded. The corrected measurements of thrust for unheated flow showed no variation with cell pressure below 10^{-1} Torr. On the other hand, the corrected thrust for heated flows did show a variation with cell pressure above 10^{-3} Torr. Because the Reynolds numbers for the cold- and hot-flow tests were of the same magnitude, the nozzle momentum explanation for the back-pressure effect seems unlikely.

Temperature measurements, taken on the surface of the laboratory-model resistojet, indicate that the effect was the result of higher heat loss from the thruster at cell pressures above 10^{-3} Torr. As the cell pressure increased above 10^{-3} Torr, the surface temperatures of the radiation shielding decreased (as did the nozzle temperatures), indicating that natural convection was cooling the surface of the thruster. However, as the ambient pressure rose above 10^{-2} Torr, the shielding temperatures increased. This was thought to be the result of increased convection between layers of the radiation shielding.

The pitot pressure measurements taken in the nozzle exit plane of the laboratory model also indicate the loss in thrust at higher cell pressures was not the result of a nozzle momentum effect. Some noticeable variation in the profile with test-cell pressure would be anticipated if the loss in thrust was primarily a flow phenomenon. No difference in pressure profiles was observed for the different operating conditions investigated.

Engineering-Model Resistojet

A smaller amount of data was taken with the engineering-model thruster. However, based on the data taken, the measured loss in thrust at higher cell pressures appears to be the result of two different phenomena: increased heat transfer from the outer surface of the thruster from natural convection and an interaction between the ambient gas in the test facility with the flow in the nozzle.

Although the surface temperature measurements for the engineering-model thruster were less extensive than for the laboratory model, the data indicate similar thermal behavior. The behavior at locations 1 and 2 was the same as that on the outer surface of the radiation shielding of the laboratory-model thruster. The temperatures decreased as the cell pressure increased from hard vacuum until convection between layers of the radiation shielding became significant, which caused the temperature to rise. At location 3, a location heated primarily by conduction, the temperature decreased with increasing cell pressure in a manner analogous to that of the laboratory-model nozzle.

Unlike the laboratory-model thruster, corrected thrust measurements for the engineering-model thruster for unheated flow were not constant with cell pressure (see Fig. 7). Therefore, although increased heat loss seemed to cause a decline in thrust at higher cell pressures, another effect seemed to contribute as well.

If it can be assumed that the cold-flow thrust data could be approximately corrected to the hard vacuum value providing the correct exit area was used, an effective exit area can be calculated at each cell pressure. At a pressure of 10^{-2} Torr, the effective exit area was essentially the area at the exit of the trumpet section of the nozzle. As the cell pressure was increased, the effective nozzle exit area decreased. This suggests the flow was not fully expanded in the nozzle, possibly as a result of separation.

Pitot pressure measurements taken in the exit plane of the nozzle indicate that the decline in thrust with increasing cell pressure may have been partially attributable to flow separation. The pressure surveys showed that the core of the flow was unaffected by the ambient conditions providing the nozzle flow was not overexpanded. Overexpanded operation was easily detected by a spike in the profile, indicative of the presence of a shock wave. The pitot pressures were found to be very low in the outer two-thirds of the nozzle exit plane. The pressures in this region were essentially equal to the ambient pressure, indicating separation. Speculated separation point movement toward the nozzle throat with increasing cell pressure could not be verified since the pressure measurements were made only at the exit plane and at discrete distances from the centerline.

More detailed pitot pressure surveys were conducted in a hard vacuum using this same resistojet by Carney and Bailey.[23] Their results showed the nozzle was free of shocks at the lowest test-cell pressures. However, extensive testing with different nozzle configurations has indicated that thrust measurements may not be wholly representative of the performance in space at higher cell pressures due to the presence of shocks.[24] This conclusion was based on numerous pitot pressure surveys at a number of different cell pressures. The results of their pressure surveys were similar to those reported here.

A final point that should be mentioned concerns the fact that the flow rate in the tests was about half of the design flow rate of the thruster due to facility constraints. Thus, the nozzle was operating with a lower inlet pressure and at a lower throat Reynolds number than it would be in an actual application. This illustrates a difficulty in conducting performance tests on these devices at suitably low pressures.

Conclusions

From tests performed on two resistojets at various test-cell pressures, it is concluded that the decrease in performance at higher test-cell pressures is a significant effect. The results further indicate that the effect is design dependent. Factors such as the amount of radiation shielding and nozzle geometry were found to be important. From thermocouple measurements, it was evident that heat transfer from each thruster increased at higher test-cell pressures. For the engineering-model thruster, there was evidence that the test-cell pressure also affected the nozzle flow.

Because the back-pressure effect seems to be design dependent, there may not be a general way of correcting performance of small thrusters as a function of test-cell pressure. Obtaining accurate performance data may require an adequately pumped facility with a sufficiently good vacuum to minimize back-pressure effects. Convective heat loss was found to be minimized by testing in test-cell pressures below 10^{-3} Torr. Because nozzle area ratio dictates the pressure whereby momentum effects such as flow separation, shocks, and pressure feedback through the subsonic boundary layer are present, the required test-cell vacuum to obtain accurate performance data will vary. The engineering-model thruster with its very large area ratio required a vacuum pressure below 10^{-4} Torr to obtain credible performance data.

Nozzle momentum effects were assessed from tests with unheated flow to minimize any heat transfer effects. These tests gave an indication on the range of vacuum pressures that affected the nozzle flow. Thrust for the laboratory-model resistojet could be corrected to the high-vacuum value up to test-cell pressures of 10^{-1} Torr by merely accounting for the pressure force on the exit area. Thrust measurements for the engineering-model resistojet, on the other hand, could not be corrected, indicating that the flow was affected by the test-cell pressure to much lower levels. If unheated flow measurements cannot be corrected, in all likelihood flow momentum effects will be present for heated flow as well. Detailed exit-plane flow measurements would provide more quantitative information on the interaction between the flow and the test-cell pressure.

In conclusion, to obtain credible performance data on resistojets in pumped facilities, a conservative estimate is that vacuum pressure should be maintained at 10^{-4} Torr or lower to minimize any back-pressure effects. If tests with unheated flow indicate that the test-cell pressure affects the nozzle flow only at levels above 10^{-3} Torr, then accurate performance data may be obtained at pressures up to 10^{-3} Torr.

Acknowledgment

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