Vacuum Chamber Pressure Effects on Thrust Measurements of Low Reynolds Number Nozzles

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Tests were conducted to investigate the effect of vacuum-facility pressure on the performance of small-thruster nozzles. Thrust measurements of two converging-diverging nozzles with an area ratio of 140 and an orifice plate flowing unheated nitrogen and hydrogen were taken over a wide range of vacuum facility pressures and nozzle throat Reynolds numbers. In the Reynolds number range of 2200 to 12,000, there was no discernable effect of ambient pressure on thrust below an ambient-to-total-pressure ratio of 1×10^{-3}. In nearly all cases, flow separation occurred at a pressure ratio of about 1×10^{-3}. This was the upper limit for obtaining an accurate thrust measurement for a conical nozzle with an area ratio of 140.

Nomenclature

A_e = area of nozzle exit plane
A^* = nozzle throat area
d^* = nozzle throat diameter
F_c = measured thrust corrected for the ambient-pressure force
F_m = measured thrust at finite ambient pressure
F_v = vacuum thrust or thrust measured at near-space conditions
g = acceleration of gravity
I_{sp} = vacuum specific impulse, $F_v/\dot{m}g$
$\dot{m}$ = mass flow rate
P_a = ambient or vacuum facility pressure
P_e = static pressure of flow at nozzle-exit plane
P_0 = nozzle chamber total pressure
Re = throat Reynolds number, $4\dot{m}/d^*\mu\pi$
u = nozzle exit velocity
γ = ratio of specific heats
μ = viscosity at nozzle chamber total temperature

Introduction

AUXILIARY propulsion for applications involving low-Earth and geosynchronous orbit missions as well as planetary flights is usually provided by small thrusters. In particular, North/South station-keeping of many geosynchronous satellites is done with thrusters in the 0.2-0.4 N thrust range. Performance calibration of these thrusters is generally undertaken in vacuum facilities with ambient pressures in the range of a few hundred micrometers of mercury. Relatively high propellant flow rates usually preclude the use of diffusion pumps and large cryo-pumped facilities are not widely available. Hence, tests are usually conducted in vacuum chambers with ambient pressures considerably higher than space vacuum.

The thrust measured in a finite ambient pressure, assuming uniform properties at the nozzle exit, is given by

$$F_m = \dot{m}u + (P_e - P_a)A_e \tag{1}$$

and the thrust in vacuum is

$$F_v = \dot{m}u + P_eA_e \tag{2}$$

Therefore the thrust measured in finite ambient pressure corrected to vacuum conditions is given by

$$F_c = F_m + P_aA_e \tag{3}$$

Equation (3) should yield the correct space-vacuum thrust providing that the ratio of ambient pressure to nozzle inlet total pressure (P_a/P_0) is sufficiently low so that shock waves are not present in the nozzle. There is, however, indication that the ambient pressure may affect thrust (corrected for the ambient pressure force) even at levels well below the shock point. This effect was demonstrated by several investigators[1-3] who found significant variation in thrust over a range of vacuum facility pressure from about $1\times10^{-4}-1$ torr where the range of P_a/P_0 was well below the point where shocks would be present. Page et al.[1] and Yoshida et al.[2,3] found an appreciable variation in thrust with vacuum chamber pressure using hydrogen and ammonia resistojets. In their work, a 17-19% degradation in thrust occurred when the ambient pressure was varied from about 5×10^{-4} to 1 torr after accounting for the ambient pressure force over the nozzle exit as well as recirculation effects in the vacuum chamber. Their 45 mN hydrogen and ammonia resistojets were operated at throat Reynolds numbers of 400 and 800, respectively. They conjectured that the vacuum chamber pressure affected the nozzle flow through the subsonic portion of the boundary layer. The thrust degradation has also been attributed to convective heat loss from the thrusters that occurs only when the ambient pressure is above a certain level.[4] This effect may possibly explain the step-like change in thrust with pressure exhibited in Refs. 1 to 3.

Rothe[5] did a detailed investigation of low-Reynolds number nozzle flow over a range of Reynolds numbers from 50-780. He measured density and temperature distributions in the nozzle flowfield using an electron beam method. He also determined shock patterns and flow separation by flow visualization. His tests were conducted with unheated nitrogen flowing through two conical nozzles, each with a 20 deg half-angle and area ratio (A_e/A^*) of 66; and each had a different throat diameter. Rothe's data showed that at a Reynolds number of 50, the flow on the nozzle axis decelerated to slightly less than Mach 1 at the exit plane.

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Density profiles at various axial stations in the nozzle illustrated that the flow was fully viscous with no evidence of an inviscid core. At a Reynolds number of 300, the flow was characterized by a narrow inviscid core enveloped by a thick viscous outer layer that extended to the walls. The inviscid core gradually dissipated until it was no longer evident at the exit plane although the center-line flow remained supersonic.

In investigating the effect of ambient pressure on the flow, Rothe showed that at a Reynolds number of 780, an ambient-to-total-pressure ratio of 3×10^{-3} was too high to maintain full flow in the nozzle. An oblique shock was present upstream of the nozzle exit and the flow was separated from the wall. As the ambient pressure was raised further, the separation point moved farther upstream.

Rothe's investigation showed that the low-Reynolds-number flow in a converging-diverging nozzle is characterized by a large viscous outer region part of which is subsonic and a narrow inviscid supersonic core. Hence at low Reynolds numbers the ambient pressure could conceivably affect the flow through the subsonic outer region and may explain or at least contribute to the effect exhibited in Refs. 1 to 3. Rothe's work also showed that as the Reynolds number was increased, the flow more closely resembled isentropic flow and shock waves were present when the flow had to adjust to a high ambient pressure.

The separation phenomenon in larger rocket nozzles has been thoroughly investigated as in, for example, the data of Campbell and Farley.[6] Their work was done at throat Reynolds numbers in excess of 100,000. Summerfield[7] deduced an empirical relationship for separation from work with nitric acid-aniline rockets where the static pressure immediately upstream of the shock is about 0.36 the value of ambient pressure.

To further investigate the effects of ambient pressure on supersonic, viscous flow and the implications of testing small thrusters in a finite ambient pressure, tests were conducted with several nozzles on unheated nitrogen and hydrogen over a Reynolds number range of 700 to 12,000. Thrust was measured at various vacuum facility pressures ranging from $3\times10^{-4}-1$ torr. The measured values of thrust corrected for the ambient-pressure force were compared to the deep-vacuum (3×10^{-4} torr) value in an attempt to investigate the range of Reynolds numbers where the ambient pressure might have a significant effect on thrust as exhibited in Refs. 1-3. An attempt was also made to investigate the effect of Reynolds number on the point where the flow begins to separate within the nozzle from the onset of shock waves. This effort was undertaken to help define where thruster test data taken in a finite ambient pressure can be accurately corrected to space-vacuum conditions.

Apparatus and Procedure

Two converging-diverging nozzles and an orifice plate were used in the tests. Table 1 lists nozzle dimensions, pressures, and flow rates. Nozzle A was similar to the nozzle on the TRW High Performance Electrothermal Hydrazine Thruster (HiPEHT)[8] and had an area ratio of 147. Nozzle B had a simple conical shape with a relatively large throat diameter and was operated at nearly the same flow rates as nozzle A to achieve lower Reynolds numbers. Nozzle B initially had an area ratio of 140 and was cut down to an area ratio of 38 for subsequent tests. The orifice plate had a conical inlet with a 45 deg half-angle.

Thrust measurements were made on a thrust stand that consisted of a horizontal mounting plate supported by four flexure plates.[8] Force in the horizontal direction either from thrust or application of calibration weights was measured by a strain-gage load cell. Propellant was fed to the thrust stand in a 3.2 mm (1/8 in.) diam. thin-wall, stainless steel tube that acted as a fifth flexure. Thrust-stand tares were highly reproducible and load-cell drift was insignificant for operation with unheated propellants. The estimated precision of the thrust measurement is about ±0.4 mN. The uncertainty in the thrust measurement ranged from $\pm0.5\%$ at 75 mN to $\pm1.7\%$ at 22 mN which was the range of thrust values for the tests.

Windage effects, or the circulation of gases in the test facility, produced a thrust-stand deflection opposing the direction of nozzle thrust. Some of the thrust stand members apparently act as a "sail" in the circulating gas environment.[1] The windage effect was examined by flowing gas through the orifice plate which was located very near but disconnected from the thrust stand mounting plate. Thrust stand deflections were monitored at the flow rates of interest over a vacuum facility pressure range of $10^{-4}-10$ torr. The largest windage effects occurred at ambient pressure of about 0.05 torr. The maximum thrust correction for windage was 1.5% for nitrogen and 3% for hydrogen. The windage corrections at ambient pressures $<1\times10^{-3}$ torr and >0.3 torr were always less than 1%.

Gas flow rates were measured with mass-flow-rate transducers which used a heated capillary tube to relate thermal changes to mass flow rate and the gas heat capacity. The flow transducers were calibrated with either air or nitrogen using a volume displacement method. The uncertainty in the nitrogen flow rate was estimated to be $>2\%$. A flow rate calibration for hydrogen was obtained using gas conversion factors supplied by the transducer vendor. Thus a slightly greater uncertainty exists in the hydrogen flow rate measurement.

The nozzle inlet pressure for nozzle B was directly measured. The inlet pressure for nozzle A was assumed to be between the line pressure and the minimum inlet pressure calculated assuming a thrust coefficient F_v/P_0A^* of 1.6. A value of 1.6 was based on analysis and experiment from Refs. 9 and 10.

The tests were conducted in a vacuum chamber measuring 4.6 m diam by 19 m long.[11] The pumping system is com-

Table 1 Thruster and orifice plate parameters

	Throat diam, mm	Nozzle half angle, deg	Area ratio	Hydrogen Pressure, N/cm^2	Hydrogen Flow rate, mg/s	Nitrogen Pressure, N/cm^2	Nitrogen Flow rate, mg/s
Nozzle A	0.64	21	147	10.7[a]	9.8	10.4[a]	38.3
				19.5[a]	19.6	20.3[a]	78.6
				26.8[a]	27.1	26.6[a]	104
Nozzle B	2.06	20	140,38	0.50[b]	9.8	0.55[b]	38.3
				1.01[b]	19.6	1.09[b]	78.6
				1.41[b]	27.1	1.41[b]	104
Orifice plate	0.76	—	1	5.8[a]	9.8	5.6[a]	38.3
				10.0[a]	19.6	10.4[a]	78.6
				13.4[a]	27.1	13.4[a]	104

[a]Line pressure. [b]Chamber pressure.

prised of 20 oil diffusion pumps with four lobe-type blowers installed in parallel, followed by four rotating piston-type roughing pumps. Vacuum chamber pressures in the vicinity of the thrust stand were measured with a hot cathode ionization gage for pressures less than 3×10^{-4} torr, a cold cathode gage from $10^{-4}-0.2$ torr, an Alphatron gage from $10^{-2}-0.5$ torr, and a bourdon-tube gage for pressures >0.5 torr. The indicated pressures were corrected for gage sensitivity to propellant type. The uncertainty in the ambient pressure (P_a) measurement below 0.5 torr was estimated to be $<\pm20\%$. The uncertainty in the pressure ratio (P_a/P_0) for nozzle A was $<\pm40\%$ and $<\pm20$ percent nozzle B.

A typical plot of thrust vs ambient pressure for nozzle A with hydrogen is shown in Fig. 1. The open symbols are the direct thrust measurements F_m and the solid symbols are F_c which is corrected for the ambient pressure force.

The diffusion pumps could maintain operation at pressures up to 4×10^{-4} torr for 0.1 g/s of nitrogen and 9×10^{-4} torr for the 0.03 g/s of hydrogen. A flow rate of 0.1 g/s of nitrogen corresponded to a thrust of about 70 mN.

Results and Discussion

The ratio of measured-to-vacuum thrust for the two converging-diverging nozzles is presented for throat Reynolds numbers of 700-12,000 as a function of P_a/P_0. Since $\dot{m}$, d^*, P_a, and P_0 were all varied in the tests, the Reynolds number based on throat diameter and the pressure ratio, P_a/P_0, were chosen as the indepenent variables. In this case, measured thrust refers to the thrust measured at a particular vacuum chamber or ambient pressure. Vacuum thrust is defined as thrust measured in deep vacuum ($P_a<5\times10^{-4}$ torr).

For reference, thrust measurements with the orifice plate were taken over a range of ambient pressures. The ambient pressure had no effect on the thrust measurements. For nitrogen, the thrust varied less than ±2 percent over a range of pressure ratios of $10^{-6}-10^{-3}$. The thrust was nominally 42 mN at a flow rate of 0.0786 g/s.

Figures 2 and 3 show the effect of ambient pressure on thrust for nozzle A. Figure 2 shows the data taken with hydrogen and Fig. 3 the data with nitrogen. The open symbols are the actual measurements and the solid symbols are the measurements corrected for the ambient-pressure force. At pressure ratios $<3\times10^{-5}$ the ambient-pressure force is negligible. At Reynolds numbers from 2000-12,000 there is no discernable effect on thrust below an ambient-to-total pressure ratio of about 1×10^{-3}. Below this pressure ratio, the corrected thrust is generally within $\pm2\%$ of the vacuum thrust.

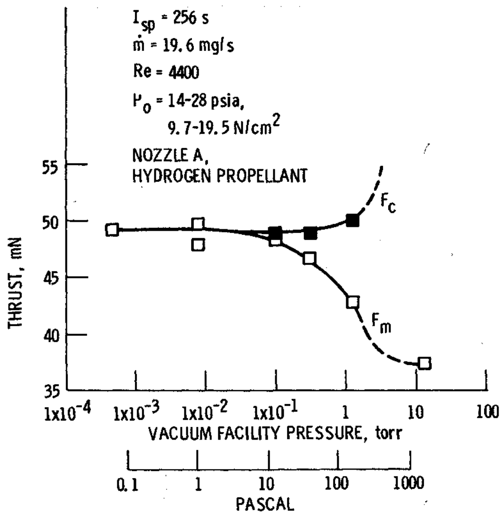

Fig. 1 Typical plot of measured thrust vs vacuum facility pressure.

Above a pressure ratio of 1×10^{-3}, there is an appreciable change in the corrected thrust attributable to shocks standing in the nozzle. When shocks stand in the nozzle, the thrust ratio (F_c/F_v) will exceed 1.0 if F_m is corrected using the nozzle exit area since the flow now has an effective area less than the nozzle exit area. F_m is thus overcorrected. The criterion that was used to determine the onset of flow separation, or the point where a shock moves into the nozzle, was the point where F_c/F_v just started to exceed 1.0. This point was considered the upper limit for testing a nozzle designed for supersonic operation in space since the thrust measured at higher pressure ratios cannot be corrected to vacuum conditions.

From the solid symbols in Figs. 2 and 3, it appears that flow separation sets in at about a pressure ratio of 1×10^{-3}, independent of the Reynolds number. As a point of reference, from simple isentropic-flow calculations and Summerfield's criterion, an oblique shock will stand at the exit of a nozzle with an area ratio of 140 at an ambient-to-total pressure ratio of about 4×10^{-4}. Since an isentropic expansion yields a lower static pressure than that of a viscous flow, a lower value of P_a/P_0 would be expected from such a calculation.

Figures 4 and 5 display the ratio of measured-to-vacuum thrust for nozzle B as a function of P_a/P_0. For nozzle B the

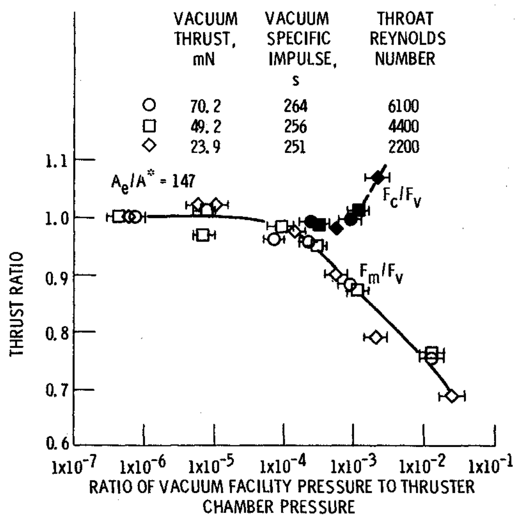

Fig. 2 Effect of vacuum facility pressure on thrust for nozzle A using hydrogen.

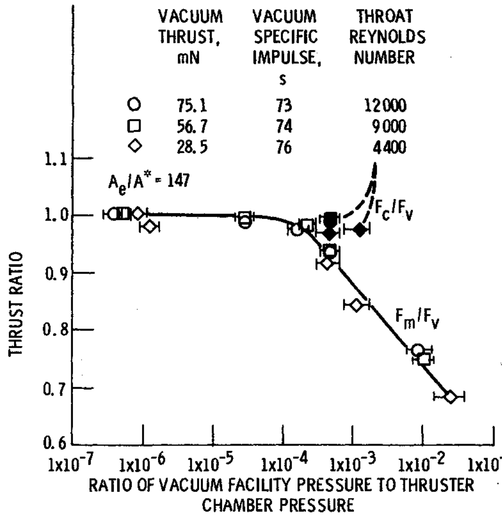

Fig. 3 Effect of vacuum facility pressure on thrust for nozzle A using nitrogen.

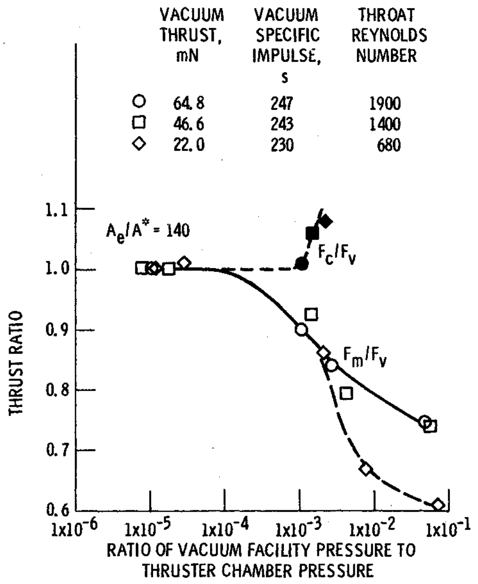

Fig. 4 Effect of vacuum facility pressure on thrust for nozzle B using hydrogen.

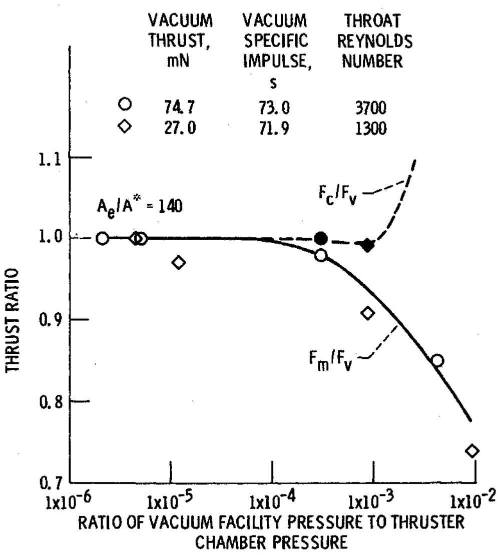

Fig. 5 Effect of vacuum facility pressure on thrust for nozzle B using nitrogen.

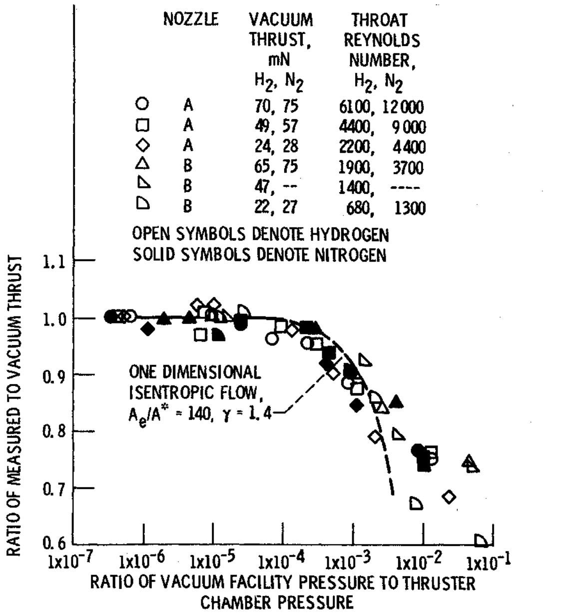

Fig. 6 Comparison of thrust ratio for various thrusters and propellants.

Reynolds number ranged from 680 to 3700. In the case of nozzle B there is insufficient data to discern any effect of ambient pressure on thrust at pressure ratios below the point of separation. The vacuum facility could not provide a diffusion-pumped environment at the low pressure ratios of interest because of the relatively high flow rates in the nozzle. The point of flow separation however does appear to occur at about the same point as for the higher Reynolds number flows of nozzle A.

When nozzle B was cut down to an area ratio of 38:1, flow separation occurred at a higher pressure ratio of about 3×10^{-3} (not shown in the figures). As expected a higher pressure ratio was required to cause a shock to stand in the nozzle of lower area ratio.

Figure 6 contains most of the data from Figs. 2 to 5 in a plot of thrust ratio vs pressure ratio. Also shown is the isentropic-flow calculation of F_m/F_v as a function of P_a/P_0 for an area ratio of 140. For $10^{-4}<P_a/P_0<10^{-3}$, the calculated values of F_m/F_v are generally 4-9% higher than the measured values. The difference between the calculated and measured values may be attributed to the relatively large uncertainty in P_a/P_0. At values of $P_a/P_0>10^{-3}$, a shock stands in the nozzle and the isentropic calculation of F_m/F_v is no longer valid without considering the pressure rise across an oblique shock.

Concluding Remarks

Thrust measurements of two converging-diverging nozzles and an orifice plate flowing unheated nitrogen and hydrogen were taken over a wide range of vacuum facility pressures and Reynolds numbers. The purpose of the tests was to investigate the effect of vacuum facility pressure as a function of Reynolds number on the performance of small nozzles designed to operate in space vacuum.

In the Reynolds number range of 2200-12,000, there was no discernable effect of ambient pressure on thrust below an ambient-to-total pressure ratio of 10^{-3}. In nearly all cases, flow separation occurred at a pressure ratio of about 1×10^{-3}. This was the upper limit for obtaining an accurate thrust measurement with the conical nozzles having an area ratio of 140. Tests with a nozzle of smaller area ratio moved this point to a slightly higher pressure ratio since a higher ambient pressure is required to cause a shock to stand in the nozzle.

Further investigation of the effect of ambient pressure on thrust will require that additional tests be performed using heated flow at lower flow rates to achieve lower Reynolds numbers and ambient pressures than were reported in this paper. Such work might also establish the sensitivity of ambient convective heat transfer effects on the thrust produced by small thrusters operated at ambient pressures typical of most test facilities.

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