Performance of High-Area-Ratio Nozzle for a Small Rocket Thruster

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Theoretical estimates of supersonic nozzle performance were compared to experimental test data on nozzles with area ratios of 100:1 (conical) and 300:1 (optimum contour) and on 300:1 nozzles cut off at 200:1 and 100:1. These tests were performed on a 5 lbf monopropellant hydrazine thruster with chamber pressures of 25–135 psia. The analytic method used was the conventional inviscid method of characteristic with a correction for laminar boundary-layer displacement and drag. Replacing the 100:1 conical nozzle with the 300:1 contoured nozzle resulted in an improvement in thrust performance of from 0.74% at chamber pressure of 25 psia to 2.14% at chamber pressure of 135 psia. The data confirm that conventional nozzle design techniques are applicable even where the boundary layer is laminar and displaces as much as 35% of the flow at the nozzle exit plane.

Introduction

PERFORMANCE studies showed that a significant fraction of a desired mass reduction goal in a spin-stabilized communications satellite could be met by improving the thrust efficiency of the main stationkeeping thrusters. The monopropellant thruster,[1] configured for the axial thruster location, has a 15 deg half-angle conical nozzle with an area ratio of 100:1 (ratio of exit area to throat area). A contoured nozzle with an area ratio of 300:1 was developed to replace it. This paper presents comparisons of the thrust performance with the baseline, prior tests, and theory.

Rao[2] devised an elegant solution to the problem of contouring for maximum thrust the supersonic portion of large rocket engine exit nozzles. In small rocket engines, such as the 5 lbf thruster, the boundary layer displaces more of the nozzle flow area; hence, the nozzle optimization technique may be questioned. The objective of this paper is to present experimental verification that the Rao technique can be applied to small nozzles. The data confirm the theoretical computations of the nozzle contour and performance, which has been extended to cases where the boundary layer displaces as much as 35% of the nozzle exit flow area.

Design Analysis

The design analyses were performed with Software Engineering Associates (in Carson City, NV) using their versions of the Rao nozzle optimization program, the TDK two-dimensional, chemical kinetic, inviscid, supersonic nozzle program,[3] and the BLM boundary-layer analysis program[3] with the laminar flow option. The Rao program requires use of a constant specific heat ratio value. This ratio was chosen so that the mean Mach number on the last right running characteristic line, which is the control surface of the optimized supersonic flowfield,[2] was the same for the constant specific heat ratio and variable properties cases.

The contour of the inviscid core flow region was obtained using the Rao program with the exit area ratio and length fixed. The TDK program was run (using frozen flow gas properties) to obtain the core flow performance. The BLM boundary-layer program provided the displacement thicknesses and thrust correction necessary to obtain the corrected nozzle contour and thrust performance. This algorithm was repeated for different inviscid core area ratios and nozzle lengths until the minimum nozzle length was obtained for a boundary-layer corrected area ratio of 300:1. The nozzle extension contour is given in Table 1.

The 300:1 area ratio for the contoured nozzle was chosen as a compromise. The maximum performance occurs at a somewhat larger area ratio. This choice of area ratio avoids excessive weight and volume in the modified thruster and decreases the requirements for propulsion test facility pumping capacity.

The original 100:1 area ratio nozzle, shown in Fig. 1, has a conical convergent section with a 70 deg half-angle merging into a throat with a 0.185 diameter and a wall curvature profile with a 0.173 in. radius. The divergent section is a 15 deg half-angle cone with a sharp corner at the throat/divergent cone juncture. The nozzle is made from a cobalt-base (L605) alloy.

The convergent section of the desired contoured nozzle is identical to the original nozzle. The wall profile at the throat is carried through beyond the throat with the radius of 0.173 in. to form a conical section to an area ratio of 10 and a half-angle of 29 deg 15 min. This angle corresponds to the secant through the optimal contour. The nozzle extension is attached to this short conical nozzle and is optimally contoured from an area ratio of 10:300. The stub exhaust nozzle is made of a cobalt (L605) alloy. The contoured nozzle extension is held to the short conical nozzle by a split compression ring and a retaining nut. The nozzle extension, retaining nut, and split rings are all made of titanium 6A14V. This method of attaching the nozzle extension was successfully used in the HE-11 thruster, which was used on the Pioneer Venus spacecraft. Figure 1 shows the modified thruster as the prototype 300:1 nozzle.

In addition to the original nozzle and the improved performance 300:1 contoured nozzle, third and fourth nozzles were fabricated. These nozzles were identical to the 300:1 nozzle, except they were cut off at area ratios of 200:1 and 100:1, respectively. These contoured nozzles are not optimally

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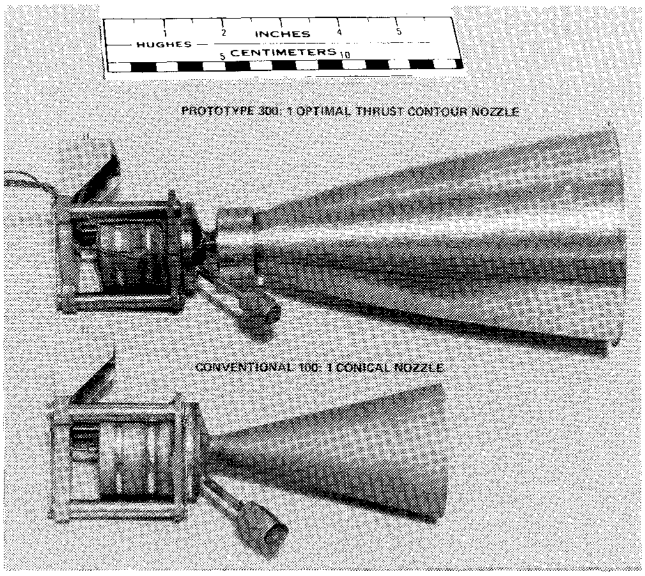

Fig. 1 Thrust chamber assemblies used in nozzle performance tests.

Table 1 Coordinates of interior surface optimal nozzle extension

	Axial position, in.	Wall radius, in.
0	0.0000	0.0925
1	0.4000	0.2914
2	0.6000	0.3851
3	0.8000	0.4695
4	1.0000	0.5457
5	1.2000	0.6155
6	1.4000	0.6808
7	1.6000	0.7423
8	1.8000	0.8003
9	2.0000	0.8554
10	2.2000	0.9077
11	2.4000	0.9577
12	2.6000	1.0057
13	2.8000	1.0517
14	3.0000	1.0961
15	3.2000	1.1388
16	3.4000	1.1801
17	3.6000	1.2200
18	3.8000	1.2587
19	4.0000	1.2962
20	4.2000	1.3327
21	4.4000	1.3681
22	4.6000	1.4025
23	4.8000	1.4358
24	5.0000	1.4681
25	5.2000	1.4991
26	5.4000	1.5290
27	5.6000	1.5575
28	5.8000	1.5846
29	6.0000	1.6104

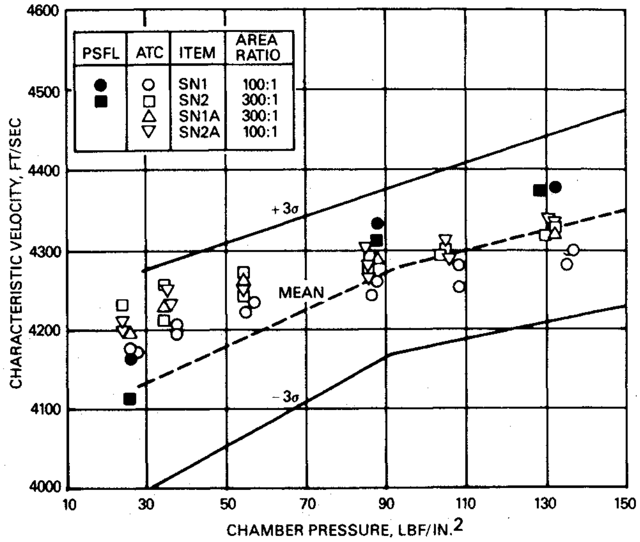

Fig. 2 Characteristic velocity data as a function of chamber pressure.

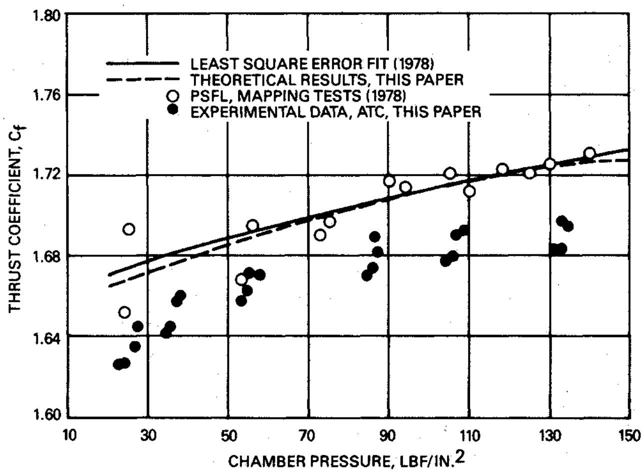

Fig. 3 Thrust coefficient data from several sources for 100:1 area ratio conical nozzle.

shaped for thrust at these area ratios. They were used as additional sources for comparison of theoretical and measured performance.

Performance Analysis

The performances of the 100:1 conical nozzle and the contoured nozzles were computed using the JANNAF reference method.[4] Computations were performed using several wall temperature distributions. For expedience, however, all the cases presented for comparison have the same wall temperature distribution, computed for a chamber pressure of 106 psia. Summary results for the optimum contour nozzle at an area ratio of 300:1 and for two additional contoured nozzles are given in Tables 2 and 3. The additional nozzles have the same contours as the 300:1 nozzle, except that the nozzles are truncated at area ratios of 200:1 and 100:1. Existing data on nozzle flow were used for the analysis, but the data were evaluated for the appropriate area ratios.

Performance Test

The performances of all the nozzles were measured experimentally in tests conducted in the Aerojet Techsystems Company (ATC) test area A facility. This test facility meets the requirements of low-pressure capability to simulate altitude conditions up to 210,000 ft with full 5 lbf thruster flow for 100 s duration. The test cell pressure must be less than half the computed static pressure on the nozzle wall at the exit plane to simulate more accurately the effect of space environment on the boundary layer. The 100 s duration permitted the radiation-cooled nozzles to reach thermal equilibrium. The thrusters were acceptance tested at the Hughes Propulsion Systems Field Laboratory (PSFL).

Thruster SN 01 was fabricated with a 100:1 conical nozzle and thruster SN 02 was fabricated with the 300:1 contoured nozzle. After the first performance characterization test series was performed on these thrusters, the nozzles were cut off at the juncture of the catalyst chamber and the exhaust nozzle. Then SN 01 was fitted with a 300:1 contoured nozzle and SN 02 with a 100:1 conical nozzle. The performance tests were then repeated. The difference in catalyst bed performance between SN 01 and SN 02 was thereby minimized, permitting isolation of the net effect on the change in thrust due to the nozzle alone. Performance of the 200:1 and 100:1 contoured nozzles were obtained by interchanging them with the 300:1 nozzle extension on thruster SN 01.

A complete acceptance test, performed on HE-54 thrusters at PSFL with SN 01 and SN 02, demonstrated that the test thrusters operated within the normal performance band required of production thrusters. An abbreviated acceptance test was then performed at ATC to demonstrate that comparable results were obtained at the two test sites. The abbreviated acceptance test was repeated at ATC after the nozzles were refitted to the chambers. The characteristic velocity C_* is defined as

$$C_* = P_c A_* g_c / \dot{m} \tag{1}$$

where P_c is the chamber pressure, A_* the exhaust nozzle throat area, and $\dot{m}$ the mass flow rate of propellant. These variables are compared in Fig. 2. The C_* performance is independent of the nozzle configuration and should be an excellent indicator of the performance of the thruster part that was not changed in this nozzle modification program.

The mean lines and the $\pm 3\sigma$ distribution were obtained from data on the last 30 HE-54 production thrusters. The C_*s for SN 01 and SN 02 measured at PSFL were in excellent agreement with the previously established statistical norms. The C_*s measured at ATC were in excellent correlation and showed that the data fall within normal bounds expected from experience with HE-54. There was no significant difference between the data taken before and after the nozzle refitting operation in either SN 01 or SN 02. Although the trends of C_* vs thrust chamber pressure measured at ATC and PSFL differed consistently, the differences were within the $\pm 3\sigma$ bands, and they were therefore considered insignificant.

Test Results

Nozzle contour modifications are best evaluated by comparing thrust coefficients C_f defined here as

$$C_{f,\text{vac}} = (F_{\text{cell}} + P_{\text{cell}} A_{\text{exit}}) / P_c A_* \tag{2}$$

where F_{cell} is the measured thrust, P_{cell} the gas pressure in the test cell, A_{exit} the area of the nozzle at the exit plane, P_c the measured chamber pressure, and A_* the throat area.

Comparison to Prior Results

Thrust coefficient data on the HE-54 thruster with the 100:1 nozzle had been obtained in 1978 using a torque balance for thrust measurements, as shown in Fig. 3. The best fit curve (shown as a solid curve) to that data has been routinely used in predicting HE-54 thruster flight performance from acceptance test data. The theoretically computed (Table 3) data (shown as a broken curve in Fig. 3) is in very good agreement with the earlier data taken at PSFL. The data from the tests at ATC are shown in Fig. 3 for SN 01 and SN 02. The data of SN 01 are about 1.4% low and that of SN 02 are about 2.0% low compared to the 100:1 conical theory and the earlier test data. Differences of this magnitude between experimental measurements taken at different facilities and by different experimenters on a nominally identical item are expected and can be attributed to small differences in calibration and accumulation of deviations from the design specifications. To demonstrate the gain in performance due to change in the nozzle contour, differences among measured results from different facilities are not material. Since such differences hinder theoretical comparisons and comparisons using prior data, the ATC data are adjusted to minimize them.

To permit comparison of theoretical calculations and the PSFL and ATC test results, the C_F data from tests at ATC with SN 01 thrusters were increased by a ΔC_F of 0.02423. All C_F data from tests at ATC with SN 02 thrusters were increased by a ΔC_F of 0.03484. The requirement that ATC data be adjusted does not suggest that ATC data are unreliable, but simply allows direct comparisons. The test data for the 100:1 conical nozzle are shown in Fig. 4 after the adjustment has been made, where the curve is the theoretically computed data.

Correlation of Theory and Data

Using all the data obtained at ATC adjusted as discussed, theory and experiment are compared in Fig. 5. The thrust coefficient results for thrusters SN 01 and SN 02 with the baseline 100:1 conical nozzle (marked 100:1 conical) and the contoured 300:1 nozzle are given for different chamber pressures. The data are reproducible and the scatter is relatively small. The theoretical increase in C_F is equaled or exceeded by the experimental C_F increase when the nozzles are changed from 100:1 conical to 300:1 contoured.

Table 2 Chamber conditions for analysis[a]

Chamber pressure, P_c, psia	Supply pressure, P_s, psia	Char. velocity, C^*, fps	Chamber temp., T_c, °R	Fraction ammonia dissoc.,[b] X	Throat wall temp., °R	Temp. adj. throat radius, R^*, in.	Throat displacement thickness, δ^*, in.	Throat momentum thickness, θ, in.	Throat Reynolds number, $Re_R{}^*$	Throat velocity coeff., C_v
25	40	4125	1700	0.900	1665	0.0935	0.001030	3.557E-4	11Θ29	0.99566
35	60	4150	1745	0.870	1700	0.0935	8.599E-4	3.142E-4	15027	0.99567
54	100	4200	1830	0.810	1763	0.0936	6.771E-4	2.729E-4	22118	0.99566
86	185	4280	1965	0.719	1852	0.0937	5.244E-4	2.426E-4	32716	0.99567
106	250	4310	2030	0.668	1888	0.0937	4.674E-4	2.293E-4	39052	0.99567
132	350	4325	2070	0.645	1905	0.0937	4.166E-4	2.112E-4	47592	0.99568

[a]Inviscid core flow computed using real gas properties method of characteristic program for real wall coordinates displaced by laminar boundary layer displacement thickness.

Table 3 Nozzle exit flow properties[a]

P_c, psia	δ^*, in.	θ, in.	$Re\delta^*$	Re_x	M_E	V_E, fps	P_E, psi	$\alpha_{p.w.}$, deg	$R_{p.w.}$, in.	C_F	I_{sp}
					Contoured 300:1						
25	0.6787	0.02042	2088.3	20768	6.741	7014.0	0.007289	0.40	0.9474	1.6732	214.518
35	0.5437	0.01764	2268.7	28164	6.794	7089.3	0.009498	0.95	1.0809	1.6838	217.188
54	0.4078	0.01493	2484.1	41121	7.166	7251.4	0.01007	3.35	1.2055	1.7082	222.993
86	0.3068	0.01291	2710.5	59650	7.058	7443.4	0.01617	3.94	1.3134	1.7302	230.165
106	0.2693	0.01220	2799.1	70152	7.070	7533.1	0.01869	4.52	1.3498	1.7437	233.585
132	0.2362	0.01118	2966.5	84797	7.009	7589.0	0.2402	4.52	1.3821	1.7514	235.428
					Conical 100:1						
25	0.3104	0.01039	1463.3	17758	5.270	6802.2	0.03271	3.52	0.6318	1.6661	213.606
35	0.2501	0.009134	1608.2	24218	5.580	6931.2	0.03210	6.18	0.6894	1.6742	215.951
54	0.1892	0.007915	1788.7	35628	5.814	7092.6	0.03718	8.44	0.7474	1.6879	220.341
86	0.1398	0.007076	1947.6	52479	5.939	7307.9	0.04832	10.24	0.7924	1.7059	226.929
106	0.1214	0.006742	2005.5	62225	5.962	7397.3	0.05551	10.95	0.8114	1.7161	229.887
132	0.1067	0.006219	2139.0	75563	5.968	7458.4	0.06696	11.30	0.8254	1.7231	231.623
					Contoured 100:1						
25	0.1731	0.007730	1205.3	20790	5.557	6859.4	0.02382	8.63	0.7638	1.6573	212.475
35	0.1445	0.006790	1357.9	28180	5.571	6929.7	0.03233	8.97	0.7958	1.6686	215.220
54	0.1132	0.005876	1531.7	40768	5.602	7057.8	0.04630	9.89	0.8281	1.6818	219.543
86	0.08585	0.005112	1707.1	59648	5.636	7257.9	0.06631	11.22	0.8491	1.7003	226.188
106	0.07534	0.004835	1770.2	70473	5.625	7340.7	0.07890	11.56	0.8621	1.7114	229.263
132	0.06671	0.004466	1890.0	84973	5.608	7397.1	0.09795	11.72	0.8704	1.7179	230.924
					Contoured 200:1						
25	0.4198	0.01448	1686.8	19516	6.119	6942.8	0.01324	2.13	0.9147	1.6676	213.800
35	0.3388	0.01250	1855.4	26673	6.274	7031.8	0.01562	3.60	0.9911	1.6820	216.954
54	0.2632	0.01079	2078.6	38573	6.354	7167.1	0.02133	4.81	1.0664	1.6995	221.855
86	0.1991	0.009383	2291.6	56206	6.451	7378.0	0.02861	6.27	1.1286	1.7225	229.136
106	0.1752	0.008891	2372.6	66299	6.498	7471.0	0.03200	7.06	1.1529	1.7355	232.484
132	0.1543	0.008165	2528.6	80246	6.495	7531.8	0.03900	7.38	1.1728	1.7433	234.339

[a]Inviscid core flow computed using real gas properties method of characteristic program for real wall coordinates displaced by laminar boundary layer displacement thickness. Subscripts "E" and "p.w." refer to properties along edge of displaced inviscid core flow.

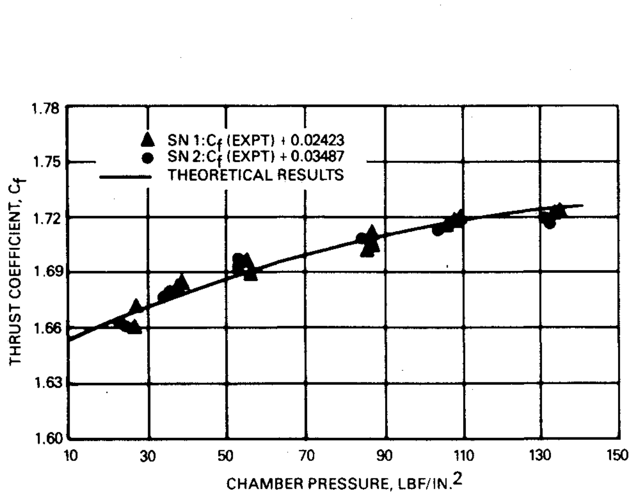

Fig. 4 Thrust coefficient data from ATC for 100:1 area ratio conical nozzle after adjustments to correlate with theoretical results.

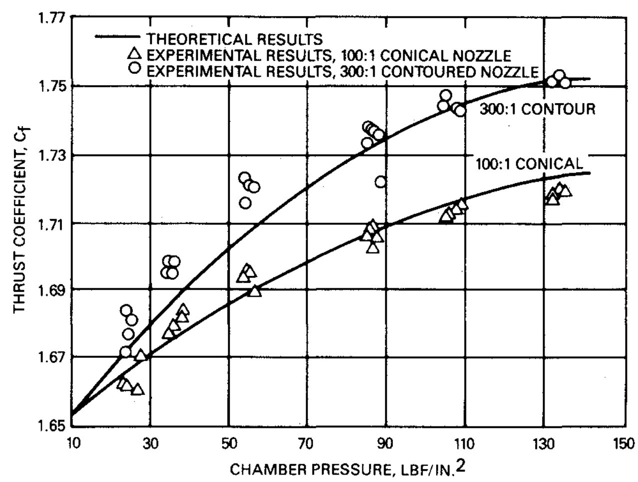

Fig. 5 Thrust coefficient from experiment and theory using all data.

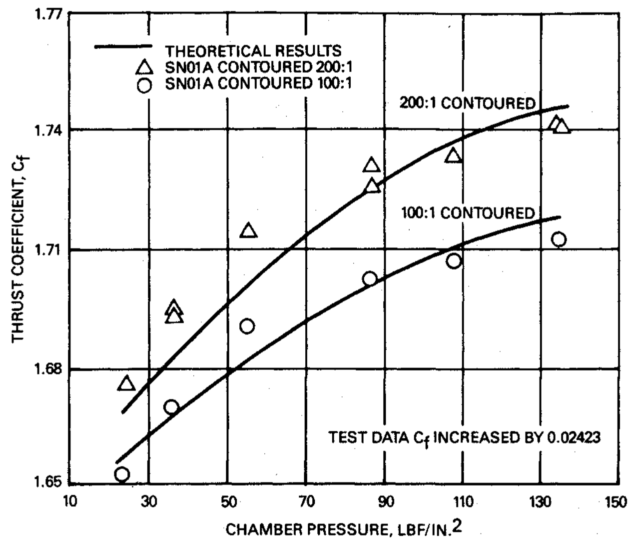

Fig. 6 Thrust coefficient from experiment and theory using adjusted data.

The adjusted data for the 200:1 and 100:1 cutoff optimal nozzles are given in Fig. 6 with the theoretical predictions. Satisfactory correlation between theoretical and experimental data is demonstrated.

Flight Qualified Design

The modified HE-54 5 lbf thruster, fabricated from the final design, is now flight qualified and assembled into the SBS F-5 spacecraft. It is essentially identical to that of the prototype model except for some details of the nozzle/nozzle extension joint. The best fit C_F vs chamber pressure equation for the 300:1 nozzle on the HE-54 thruster is

$$C_{F,\mathrm{vac}} = 1.637663 + 1.540169 \times 10^{-3} P_c - 5.145987 \times 10^{-6} P_c^2 \tag{3}$$

where P_c is given in psia.

Discussion of Results

The goal of obtaining a significant increase in the thrust performance of the HE-54 thruster was met, with a demonstrated increase ranging from 0.74% at 25 psia to 2.14% at 135 psia. This verifies that the optimization of nozzle contours is still applicable where the boundary-layer displacement can be as large as 42% of the nozzle radius at the exit. Small variations in the nozzle contour from optimum, such as those where the optimal contour was replaced with a straight conical surface between the throat radius and the nozzle extension joint, did not make a significant difference in the performance.

The test matrix for nozzle interchange was designed to minimize the effect of any possible difference between thruster SN 01 and SN 02. The existence of differences can be inferred from the thrust coefficient adjustment bias discussed above. Machining off one test nozzle and welding on another very close to the catalyst bed could have introduced disturbing influences to the nozzle contour comparison. It has been found, from detailed comparisons of chamber pressure oscillograph traces during the multiple pulse firings required in the acceptance test procedure, however, that there were no significant differences due to disturbances in the catalyst bed before and after nozzle replacement. Certainly, no significant difference could be seen in the steady-state performance, as demonstrated by the C_* characteristics shown in Fig. 2.

The adjustment in the experimental C_F data obtained at ATC by the amounts shown in Fig. 4 are applied equally to the conical nozzle and contoured nozzle. Hence, the primary purpose of the tests, which is to demonstrate the relative performance of the conical and contoured nozzles, is preserved. The agreement with theory of trend over a range of chamber pressures is excellent, for both the conical and the contoured nozzles. These results can be used to prove that conventional theoretical analysis of supersonic nozzle performance can still be used in this low thrust range. The difference between the thrust coefficient of the early Hughes tests on the 100:1 conical nozzle and the more recent ATC test results is somewhat large at 1.1% for SN 01 and 1.3% for SN 02, but this is not unexpected. These differences in thrust coefficient results could be rationalized only through a series of tedious calibration and verification tests at both facilities, which was beyond the scope of this study.

The penalty of using an incorrectly contoured nozzle is shown in the comparison of C_F for the 100:1 conical and 100:1 contoured nozzles. At low chamber pressure levels, the conical nozzle outperforms the contoured nozzle at the same area ratio.

Conclusions

Experimental tests demonstrated that the thruster with the 300:1 nozzle extension will give 0.74–2.14% performance increase over the conventional 100:1 area ratio axial thruster.

The theoretical method for the design of maximum thrust nozzle contours for high-area-ratio nozzles with corrections for a thick laminar boundary layer were validated. The predicted thrust coefficient increases are either in agreement with or slightly smaller than the experimental thrust coefficients.

It has been demonstrated both theoretically and experimentally that nonoptimally designed contoured nozzles (i.e., 100:1 and 200:1 area ratio nozzles that are cutoff versions of the 300:1 nozzle) will yield thrust that can be predicted to be no or slightly better than the baseline 100:1 conical nozzle.

The technique of cutting off the exhaust nozzle at the weld interface with the catalyst chamber and reattaching a new exhaust nozzle was demonstrated to yield no deterioration in catalyst bed performance.

It is recommended that the performance of the 300:1 area ratio nozzle thruster be based on theoretical estimates using techniques described in Ref. 4, since this is consistent with past and present test data and is an extrapolation of existing JANNAF methodology.

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