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MIXING EFFECTIVENESS TEST OF AN EXHAUST GAS MIXER

IN A HIGH BYPASS TURBOFAN AT ALTITUDE

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ABSTRACT

Thermal mixing effectiveness characteristics of an eighteen lobe, scalloped and unscalloped, partial, forced mixer were measured in a high-bypass turbofan engine. Data were also obtained without the mixer installed, i.e. free mixing. Tests were conducted at four combinations of simulated flight conditions from 0.3 to 0.8 Mach number and from 6,096 meters (20,000 ft) to 13,715 m (45,000 ft) altitude. Mixing chamber lengths of L/D=0.52 and 0.65 were tested. For this range of test conditions and mixer configurations the forced mixing effectiveness varied from 59 to 68 percent. Values of mixing effectiveness and total pressure loss were calculated from temperature and pressure data obtained at the mixer inlet and exhaust nozzle exit.

INTRODUCTION

Conservation of fuel is a stated national goal. Development or improvement of turbine engine components which contribute to fuel conservation is desired. Fuel savings potential has been ascribed to exhaust gas mixers for turbofan aircraft engines in theory and model tests, references 1-4. Simulated altitude tests of a full-scale mixer have demonstrated a reduction in fuel consumption in a low-bypass turbofan, refs. 5 and 6. To assist in the evaluation and design of mixers, and because of the paucity of published data, full-scale, altitude tests were conducted in a high-bypass turbofan

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engine. Mixing effectiveness data were obtained at similar engine operating conditions with the mixer installed, i.e., forced mixing, and without the mixer, i.e., free mixing. Tests were conducted over a range of engine speed at four combinations of simulated flight Mach numbers from 0.3 to 0.8 and altitudes from 6096 meters (20,000 ft) to 13,715 m (45,000 ft). The effect of mixing length on mixer performance was determined by varying the mixing chamber L/D from 0.52 to 0.65. The effect of scalloping the mixer chute trailing edges was investigated. Pressure and temperature data were obtained at the mixer inlet and exhaust nozzle exit.

APPARATUS

Engine

The engine used for this investigation was a TF34 two-spool turbofan. The single-stage fan pressure ratio was 1.5:1 with an airflow bypass ratio of 6.2 at sea level. The overall engine pressure ratio was 21:1. The engine installation in the altitude chamber was of the conventional direct connect configuration. The engine was fitted with a non-standard aft fan cowl which had been used in previous testing and modified for these tests. Two fan nozzles of differing contour and nominal lengths of 75 and 89 cm. (30 and 35 in.) were fabricated for this test (fig. 1). With the mixer installed, the two nozzles resulted in mixing chamber length to equivalent diameter ratios of 0.52 and 0.65. To maintain standard operating line performance, the nozzle exit area was five percent larger than standard to allow for blockage due to the nozzle exit plane rake array.

Mixer

The eighteen lobe mixer is shown schematically in figure 1 and pictorially in figure 2. It was fabricated from 0.086 cm. (0.034 in.) thick Inco 625 and weighed 9 kg. (20 lb). The mixer penetration was 0.39, that is the ratio of the lobe height at the mixer exit to the mixing chamber passage height at the mixer exit plane. The perimeter ratios, ratio of the perimeter of the mixer lobes measured at the mixer exit plane to the mixing chamber length, were 11.1 and 8.8, respectively.

Three mixer configurations were tested. An eighteen lobe, forced mixer was tested (fig. 2). This mixer was scalloped as shown by the dashed line in figure 1 and retested as shown in figure 3. A confluent, free mixer configuration was tested by removing the eighteen lobe mixer. The fan/core splitter ended at the zero datum axial location (fig. 1), at that point free mixing of the fan and core streams began. Therefore, the free mixing length to diameter ratios were 0.67 and 0.83 or 28 percent greater than the forced mixing length ratios.

Instrumentation

Engine instrumentation was identical for all tests. Pressures were recorded on individual transducers and on scanivalves. The individual differential type transducer data channel had a recording system accuracy of $\pm$0.60 percent full scale. The differential type scanivalve transducers were calibrated while in use and had a system accuracy of $\pm$0.26 percent full scale. All thermocouples were Chromel-Alumel and referenced to 339 K (610° R) ovens. System accuracy was estimated at $\pm$1.1 K (2.0° R).

Rakes witn five total pressure and five total temperature probes each were located in the core and fan streams at the mixer inlet axial plane. There were three core rakes and four fan stream rakes installed. The instrument array which measures the mixing effectiveness was composed of thirteen rakes mounted approximately 2.54 cm (1.0 in.) downstream of the nozzle exit. Cumulatively, there were 128 total pressure probes and 113 total temperature probes on these rakes.

PROCEDURE

Mixer performance was obtained at each simulated flight condition over the range of engine corrected fan speed from 70 to 100 percent. A comparison test was made at the same flight condition and speed range with the mixer removed from the engine. Upon removal, the mixer chute trailing edges were scalloped. The scalloped mixer was tested over the same flight conditions and speed range. These comparison tests were conducted with each of the two different length fan nozzles. The four flight conditions considered are presented in table I. A summary of nominal mixer operating conditions corresponding to these simulated flight conditions is shown in table II. The relationship between fan speed and exhaust nozzle pressure ratio is presented in this Table. Where practical, tests were repeated during the investigation in order to verify data repeatability.

RESULTS AND DISCUSSION

Mixing performance is presented at four simulated flight conditions over a range of engine speed from 70 to 100 percent. Data are presented for three configurations; 18 lobe mixer, scalloped 18 lobe mixer and a confluent or free mixer. Performance data for these configurations are presented for two mixing cnamber lengths. Mixer performance is expressed as thermal mixing effectiveness and mixer total pressure loss. Thermal mixing effectiveness is defined in terms of the mass-weighted, square root values of the relevant temperatures. Mixing effectiveness, in these terms, is the ratio of the difference between the actual nozzle exit stream total temperature and the calculated unmixed temperature to the difference between the calculated fully mixed stream temperature and the unmixed temperature. The actual stream temperature is an integrated value obtained from the nozzle exit rake array data. The temperature integration technique was adapted from one originated by the General Electric Company and obtained through contract NAS3-21624. The unmixed temperature represents a mass-weighted average value assuming no thermal mixing between the fan and core flow streams. The calculated unmixed and fully mixed stream temperatures were based on the experimentally obtained mixer inlet conditions. The mixer total pressure loss is defined as the difference between the measured pressure loss with the mixer installed and the loss measured when the mixer was removed. Percent total pressure loss was the difference between the mass averaged mixed total pressure at the mixer inlet plane and the area weighted total pressure at the nozzle exit divided by the mixer inlet total pressure. For these tests the area weighted exit pressure was equivalent to the mass averaged value. The measured mixer total pressure loss represents the pressure loss due to the lobed mixer plus the loss contributed by the increase in mixing above the free mixing level.

The mixing effectiveness of the 18 lobe mixer and confluent or free mixer with the 89 cm (35 in.) nozzle are presented in figure 4. With the 18 lobe mixer installed this nozzle produced a mixing chamber length to diameter ratio of 0.65. For a given simulated flight condition the mixing effectiveness values measured with the 18 lobe mixer remained nearly constant at 66 percent over the investigated range of fan speed and/or nozzle pressure ratio. At a given fan speed the mixing effectiveness did not vary appreciably over the range of selected flight conditions. Effectiveness values averaged over the speed range for each of the four flight conditions agreed within a 2.0 percent band. Comparison with a repeat set of forced mixer data for these same conditions shows a fortuitous repeatability of 0.1 percent. All of the averaged, forced mixer repeat data points taken in this investigation agreed to within 1.5 percent.

Mixing effectiveness for the confluent or free mixer is shown in the lower portion of figure 4. The data exhibited some variation with fan speed. Effectiveness values for the three high Mach number/high altitude flight conditions declined with increasing speed to minimum values near 90 percent speed and then increased somewhat as the fan speed was increased to 100 percent. At a given fan speed the effectiveness did not vary appreciably for the three high Mach number/high altitude flight conditions. For the lowest Mach number/lowest altitude condition the effectiveness values were higher in the 90 to 100 percent speed range than those values measured at the high Mach/high altitude test condition. This increase in free mixing effectiveness at the higher fan speeds for the low flight condition was also noted in two other comparable data sets. Inspection of the gas stream temperature profiles at the nozzle exit shows evidence of increased mixing at the low Mach number/low altitude condition when compared to the high Mach number/high altitude profile for the higher fan speeds. The increased mixing observed is probably due to increased shearing forces at the core/fan interface. The total pressure gradient across the interface is much steeper at the low Mach number/low altitude than at the higher altitude conditions. The increased pressure gradient and shear forces would enhance thermal mixing.

The free mixing effectiveness data appear to group about an average value of 25 percent. This value appears high for a free mixed configuration when compared to an average forced mixing effectiveness of 66 percent obtained with the same length nozzle. But when the mixer was removed to produce the free mixer configuration the core/fan splitter ended at the zero datum plane shown in figure 1. Therefore, for the 89 cm (35 in.) fan nozzle, the mixing chamber L/D for the free mixer was 28 percent greater than for the 18 lobe forced mixer. The longer mixing length may account for the relatively higher than expected free mixing effectiveness.

In figure 5 mixing effectiveness data obtained at a simulated flight condition of 0.8 Mach number and 10,667 m (35,000 ft) altitude with the 75 cm (30 in.) and 89 cm (35 in.) length fan nozzles are shown. With the mixer installed the two nozzles resulted in mixing chamber length to diameter ratios of 0.52 and 0.65. The mixing chamber length was measured from the mixer chute exit to the nozzle exit plane, and the diameter was the equivalent diameter of the net stream flow area at the mixer exit plane. An average measured mixing effectiveness of 61 percent was obtained with the short nozzle at this simulated cruise condition. With the long nozzle and hence longer mixing length the average mixing effectiveness increased to 65 percent. A four point increase in mixing effectiveness with the long fan nozzle was noted for the free mixer configuration.

The increase in mixing effectiveness due to scalloping the trailing edges of the mixer chutes is shown in figure 6 for the two nozzle lengths.

Scalloping provided a 5 to 7 percent increase in mixing effectiveness. With a mixing chamber L/D of 0.65, scalloping raised the average effectiveness from approximately 65 to 68 percent. For a mixing chamber L/D of 0.52, the average effectiveness was increased from 61 to 65 percent. It is shown that scalloping the mixer with the 0.52 L/D increases the effectiveness to 65 percent which is equivalent to increasing the mixing chamber length to 0.65 L/D for the unscalloped mixer.

The total pressure loss as defined previously is presented in figure 7 for the scalloped and unscalloped mixer with the short nozzle. Due to the inherent inaccuracy of a parameter derived from a series of small differences of measured values, each possessing a finite accuracy, the data of this figure should be considered for general level and relative values only. Attention is directed to the higher fan speed range, 90 percent and above, because the accuracy tends to improve as the speed, and therefore the absolute pressure level, increases. The level of the pressure loss due to the mixer installation and subsequent forced mixing was approximately 0.5 percent for the stated geometry and operating condition. When the mixer was scalloped, the total pressure loss was unchanged. The pressure loss differences shown in figure 6 are within the accuracy limits of the data.

SUMMARY OF RESULTS

A full-scale, altitude performance test of an exhaust gas mixer was conducted with a high-bypass-ratio turbofan engine. The following results were obtained from this investigation:

1. Forced mixing effectiveness did not vary appreciably with engine speed or over the range of simulated Mach number/altitude test conditions.
2. Average mixing effectiveness increased from 61 to 65 percent as the mixing chamber length was increased from L/D=0.52 to 0.65.
3. Mixing effectiveness increased when the mixer chute trailing edges were scalloped. Average mixing effectiveness increased 5 to 7 percent due to scalloping.
4. Maximum value of mixing effectiveness of 68 percent was attained with a scalloped, 18 lobe, partial, forced mixer with a mixing chamber L/D of 0.65 at a typical altitude cruise condition.

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TABLE I. - SUMMARY OF TEST CONDITIONS

Simulated flight Mach number	Simulated altitude		Engine inlet pressure		Engine inlet temperature		Ambient pressure	
	m	ft	N/cm²	psia	K	°R	N/cm²	psia
0.3	6 096	20 000	4.96	7.19	253	455	4.65	6.75
0.8	10 667	35 000	3.63	5.27	247	444	2.39	3.46
0.8	13 715	45 000	2.25	3.26	244	440	1.48	2.14
0.6	10 972	36 000	2.88	4.18	232	418	2.26	3.28

TABLE II. - SUMMARY OF MIXER INLET CONDITIONS

Simulated flight condition Mach no./ alt. (m)	Corrected fan speed, percent	Mixer inlet core total pressure		Mixer inlet core total temperature		Core to fan total pressure ratio	Core to fan total temperature ratio	Nozzle pressure ratio	Bypass ratio
		N/cm²	psia	K	°R				
0.3/6 096	70	5.63	8.16	656	1180	0.98	2.43	1.23	7.22
	80	6.02	8.73	700	1260	.99	2.55	1.30	6.69
	90	6.58	9.55	759	1367	1.01	2.67	1.40	6.19
	95	6.98	10.13	791	1423	1.02	2.75	1.47	5.99
	100	7.45	10.81	856	1540	1.04	2.93	1.55	5.86
0.8/10 667	70	3.52	5.11	606	1090	0.92	2.35	1.61	9.52
	80	3.95	5.73	666	1198	.95	2.52	1.75	8.23
	90	4.54	6.58	735	1323	.98	2.69	1.94	7.09
	95	4.90	7.11	781	1406	1.00	2.80	2.05	6.61
	100	5.27	7.65	833	1499	1.02	2.93	2.18	6.32
0.8/13 715	70	2.17	3.14	631	1135	0.92	2.46	1.61	9.74
	80	2.44	3.54	686	1235	.95	2.62	1.76	8.40
	90	2.81	4.07	762	1371	.98	2.81	1.94	7.26
	95	3.02	4.38	808	1455	1.00	2.93	2.05	6.86
	100	3.25	4.71	856	1540	1.02	3.05	2.17	6.51
0.6/10 972	70	2.97	4.31	601	1082	0.95	2.45	1.39	8.76
	80	3.26	4.72	649	1169	.96	2.60	1.50	8.03
	90	3.67	5.32	711	1280	.99	2.77	1.64	7.01
	95	3.94	5.72	752	1353	1.01	2.87	1.73	6.67
	100	4.23	6.13	797	1435	1.03	2.99	1.83	6.30

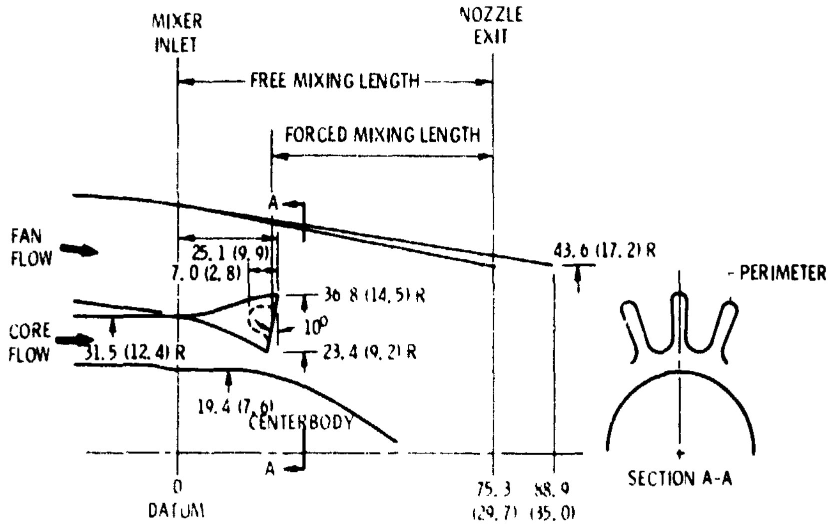

Figure 1. Cross-sectional schematic of turbofan exhaust gas mixer. Dimensions are in cm (in.).

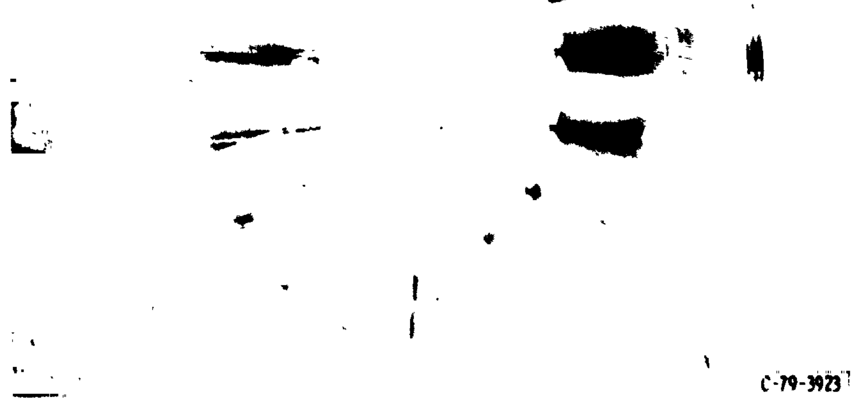

Figure 2. - Eighteen lobe mixer.

Figure 3. - Eighteen lobe mixer, scalloped.

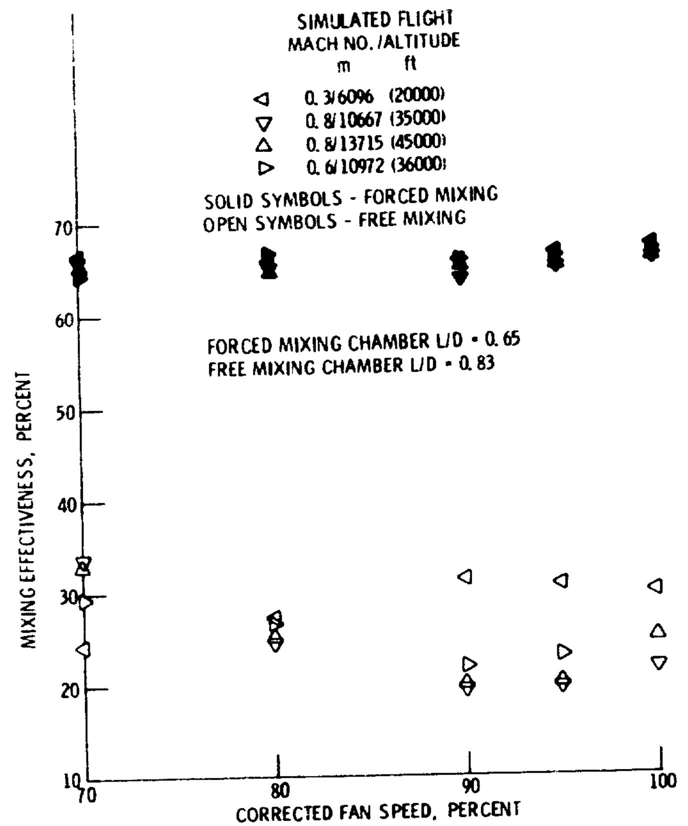

Figure 4. - Effect of simulated flight conditions on mixing effectiveness.

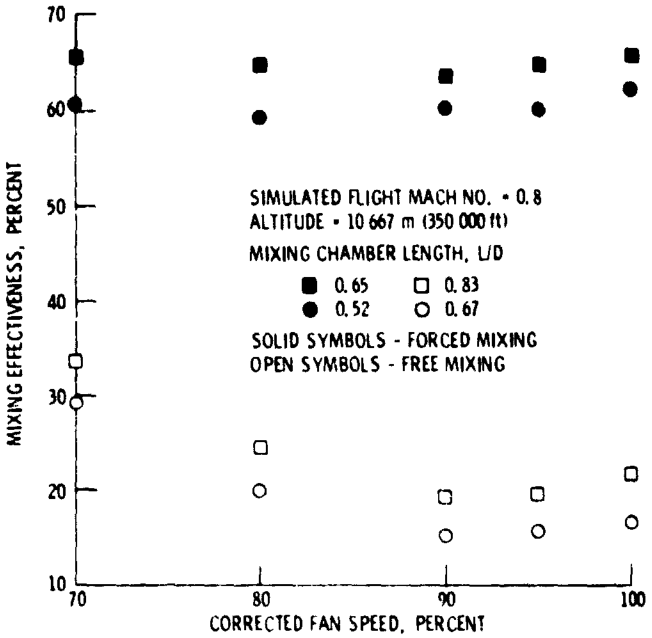

Figure 5. - Effect of mixing chamber length on mixing effectiveness.

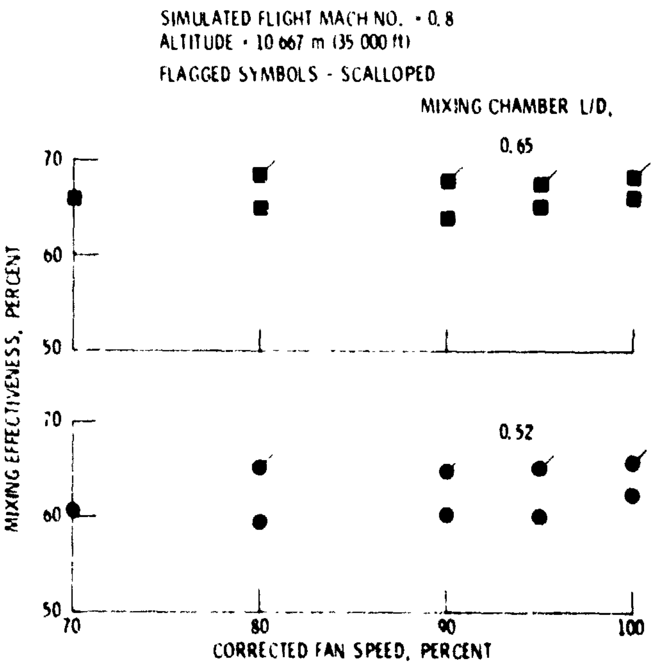

Figure 6. - Effect of scallops on mixing effectiveness.

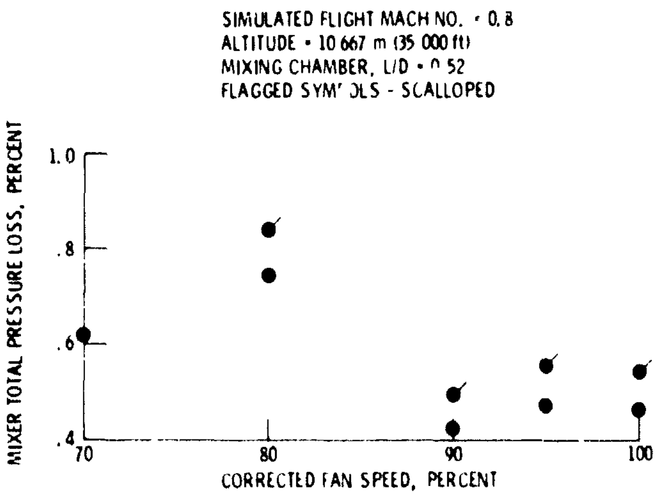

Figure 7. - Effect of scallops on mixer pressure loss.