Flow Fields of Internally Mixed Exhaust Systems With External Plug For Supersonic Transport Applications

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Commercial supersonic vehicles of the future will likely use engines with lower bypass ratios, where the design of the internal mixer will have a strong impact on the noise produced by the jet plume. Their exhaust systems may also feature external plugs to improve boattail angle for cruise performance at supersonic speeds. Currently there are no publicly available empirical noise models for such nozzle systems, and insight into their flow fields will help in creating these models. For those attempting to make large eddy simulations and other higher fidelity methods be their main prediction tool, the internally mixed exhaust system is also a good test case when going beyond simple single-stream jets. The turbulent flow statistics of several configurations previously tested for noise and shocks have been measured for flow conditions that can be used in development of empirical models and validating scale-resolving prediction tools. These measurements are presented and briefly analyzed for insights into the noise impacts from the flow impacts observed.

Nomenclature and Abbreviations

AAPL	Aero-Acoustic Propulsion Laboratory
BPR	Bypass Ratio, mass of bypass/mass of core
Djet	Jet diameter, by equivalent area
Ma	Mach number, ideally expanded, based on ambient speed of sound.
Mf	Mach number of flight stream
NATR	Nozzle Acoustic Test Rig
NPR	Nozzle pressure ratio, total pressure/ambient pressure
NTR	Nozzle temperature ratio, total temperature/ambient temperature
TKE	Turbulent kinetic energy
u, v, w	Cartesian velocity components
U,V,W	Time-averaged cartesian velocity components
Uj	Ideal jet exit velocity, fully expanded
Uf	Flight stream velocity

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I. Motivation

Flows from internally mixed exhaust systems are of practical importance, especially for performance-driven aircraft such as commercial supersonic airliners. Such aircraft will have to meet high thrust performance at cruise and low noise flying in and out of airports. For the latter requirement, the unsteady flow characteristics will be very important.

Internal mixers, usually forced lobed mixers, can be a challenge to design for performance, but their acoustic performance is especially difficult to predict. Although common in practice there has been little systematic study of mixer design and open datasets of both geometry and turbulent flow measurements are very sparse. The studies of Garrison, published in References [1–3] used early cross-stream PIV measurements from Reference [4] to substantiate their modeling of noise from internally mixed nozzles. These studies also showed how internally mixed nozzles could produce noise that involved subtle details of the design, noise features that might involve internal feedback, such as demonstrated by [5].

For an aircraft cruising at supersonic speeds, the boattail drag of the propulsion system must be kept minimal. One way of doing this is to use an external plug to fill the difference between the engine's nacelle and its station 9 area. This is especially critical if the vehicle is to have a low sonic boom signature as it will be required to fly over land. Very little jet plume data exists for internally mixed exhaust systems with an external plug, even though the increased outer shear layer created by the plug makes a significant impact on the plume.

Future design of nozzles systems would seem to rest on high-fidelity simulations, such as large eddy simulations. The accuracy of these numerical methods are being demonstrated for simple jet flows. However, it has yet to be determined if they can predict the complicated flow-sound interactions which can occur in internally mixed exhaust systems. High quality flow and acoustic data to validate simulations will be needed to complete development of simulations before they can be relied upon for design decisions.

Given the importance of internally mixed exhaust systems with external plugs for the coming supersonic transport market, and given the relatively poor understanding of the noise of such systems, a series of exhaust nozzles was designed to study them. A corresponding set of internal plug nozzles was also designed such that they shared mixers interchangeably, trying to maintain nozzle areas, area ratios, and mixing duct length. Extensive Reynolds-Averaged Navier-Stokes analysis was performed on variations of mixer and plug design to select representative test cases. Components for a matrix of nozzle configurations were fabricated and initial acoustic testing was covered in a recent paper[6]. More recent work studying the impact of flight on the noise of these configurations will be reported concurrently with this paper[7].

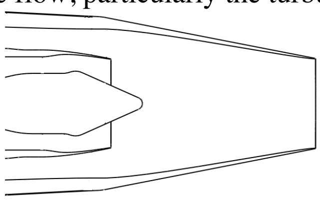
In more recent tests the same model system was used for particle image velocimetry (PIV) measurements to document the impact of the various geometric features on the flow field. This paper documents the test articles and flow conditions tested, and summarizes the measurements of the turbulent flow field. The results are organized to highlight the effects of single vs. dual stream plumes, the impact of the internal mixer, the impact of the external plug, and the impact of an external flight stream on the plumes of all of the above configurations.

II. Model Hardware

The geometric configurations of the test included combinations of plug, internal mixer, and nozzle. Configurations are first grouped as internal vs. external plug. All configurations had a nozzle exit area of 28.27in^2 or equivalent diameter *Djet* = 6.00 inch. This size has been found [8] to be large enough to represent physics of flows at the Reynolds numbers typical of aircraft engines. Each has the option of an internal axisymmetric splitter *m0* or a 16-lobed mixer *m5*. Because the combination of axisymmetric splitter with external plug was previously found to resonate and would not be of interest for engine applications, this combination was not measured with PIV. Two lengths of external plug were measured, paired with the lobed mixer. Plug *p2069* extended 11.85 inches (roughly 2**Djet)* beyond the nozzle exit and plug *p2079* extended 17.83 inches (3**Djet)*. These combinations are shown in Figure 1.

The mixing duct length, *i.e.* the distance between the exit of the splitter and the exit of the nozzle, is the same for both the internal and long-duct external plug configurations. As originally designed, all configurations were intended to have the same flow areas. In testing it was found that the difference in plugs changed the effective flow area of the core stream, thus impacting bypass ratio. Based on measured flow rates of an unheated, pressure-matched subsonic flow the bypass-to-mixer area ratio was 2.16 for the internal plug configurations and 2.83 for the external plug configurations.

It is also important to note that the external plugs drooped during hot operation, causing the flow to lose axisymmetry. In previous tests of separate flow nozzles such deformations resulted in large asymmetries in the flow, particularly the turbulent quantities.



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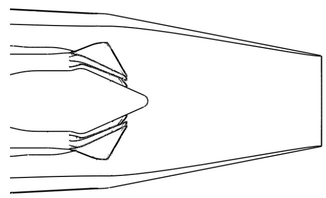

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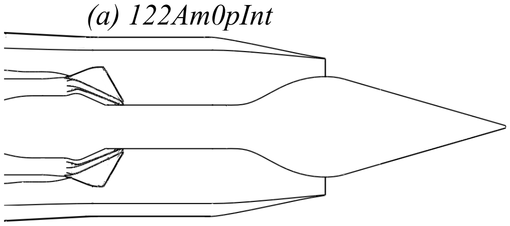
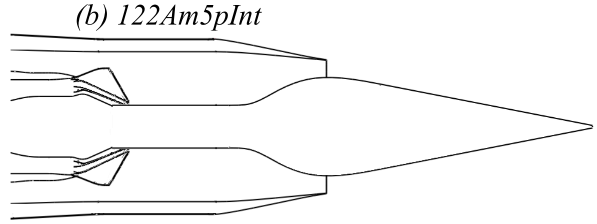


(c) 122DLm5p2069



(d) 122DLm5p2079

Figure 1 Dual-stream, internally mixed nozzles used in test. Internal plug nozzles (a) with axisymmetric splitter *m0* and (b) with lobed mixer *m5*. External plug nozzle with (c) moderate length plug *p2069* and (d) with long plug *p2079*.

III. Flow conditions

Most flow conditions measured with PIV were meant to mimic a potential two-stream engine for commercial supersonic aircraft at the FAA sideline condition, e.g. just after leaving the runway. For the PIV measurements we chose to document flow conditions with nozzle pressure ratio of 2.0, having matched core and bypass total pressures (extraction ratio = 1). Although this condition is slightly supercritical, it did not have significant broadband shock noise [9] and represents the highest speed one could likely use in commercial application. Setpoint 1200 has a slightly heated bypass stream, typical of the temperature rise of a high pressure ratio fan and a core temperature representative of current turbofan core technology. As one of the test objectives was to compare the plumes from internally mixed exhaust systems with those having a fully mixed plume, a pair of setpoints, 3200 and 4200, were created. Setpoint 4200 has both streams at the same temperature, the highest temperature the jet rig could produce on the bypass stream. Setpoint 3200 was then created to have the bypass stream unheated and the core stream at the temperature that produced the same fully mixed velocity. And finally, setpoint 70 was a matched flow condition producing an unheated, single-stream plume at acoustic Mach number Ma = 0.9 for comparison with historical data. Setpoints 1200 and 70 were also tested in different flight streams; a change in the first digit in the right-hand side of the setpoint indicates the flight stream condition. The flow conditions are given in Table 1.

During PIV image acquisition the setpoint values of nozzle pressure ratio (*NPR*) and nozzle total temperature ratio (*NTR*), along with freejet flight speed (*Mf*), were held constant to within a cumulative 0.5% error.

Table 1 Engine Cycle Matrix, specified by common nozzle pressure ratio, core and bypass total temperature ratios, and freejet Mach number.

Setpoint	*NPR*	NTR_{core}	NTR_{bypass}	*Mf*
1200	2.0	3.25	1.20	0.00
1203	2.0	3.25	1.20	0.30
3200	2.0	2.75	1.00	0.00
4200	2.0	1.31	1.31	0.00
70	1.856	1.00	1.00	0.00
71	1.856	1.00	1.00	0.10
73	1.856	1.00	1.00	0.20
75	1.856	1.00	1.00	0.30

IV. Facility

The test was conducted in the NASA Glenn Research Center's Aero-Acoustic Propulsion Laboratory (AAPL), a 65-foot radius anechoic geodesic hemispherical dome. The nozzles were mounted on a jet engine simulator, itself centered in the Nozzle Aeroacoustic Test Rig (NATR) contained in the AAPL. The NATR is a freejet wind tunnel which provided the flight stream for the engine simulator.

A turbofan engine simulator, the High Flow Jet Exit Rig, is fed by compressed air from centralized compressors, delivered to the test article through a system of manifolds, heaters, flow measuring venturis, control valves, and flow conditioners. For setpoints simulating an aircraft engine, all air streams were preheated using a mixed flow heat exchanger before being split into two streams representing core and bypass streams on an engine, independently metered and pressure-controlled, and directed to co-annular settling chambers in the rig. The innermost air stream was further heated using a natural gas combustor upstream of the engine simulator.

V. Instrumentation

The engine simulator was instrumented to record total temperature, total pressure, and static pressure at a charging station (representing engine station 7 on an engine) on all streams. In addition, mass flowrates were recorded using venturi meters. Ambient conditions in AAPL were recorded simultaneously with the flow measurements.

The heated flow streams were seeded using a pH stabilized dispersion of ~0.4μm diameter alumina particles in ethanol[10]. The stabilized dispersion of alumina was introduced into the flow well upstream of the model by atomizing the dispersion in each of the three engine streams. The ambient flow from the facility freejet was seeded using a propylene glycol fog of ~0.7μm diameter sized particles. Multiple Roscoe foggers, models 3000 and 6000, situated in the freejet ejector inlet room of NATR, produce the fog that seeds the ambient, or flight, air. At some conditions it was difficult to maintain consistently uniform seeding in the freejet flow stream, leading to low number of valid measurements in these regions.

PIV measurements were made in two configurations: two-component velocity measurements in a streamwise plane including the jet centerline, and three-component measurements in cross-stream planes. This paper will present results from the streamwise measurements. All optical equipment was mounted on a large traversing frame which moved parallel to the jet axis. The two-component streamwise plane system was implemented with a vertical light sheet coming from below the jet, aligned with the outward lobes of the mixer for configurations containing the *m5* mixer. For this reason, on configurations with an external plug, no data was obtained above the plug. For this test we required a large field of view to cover the transverse extent of the plume, which was accomplished using a 2x2 array of Princeton Instruments ES11000 cameras equipped with 180 mm focal length lenses and 8 mm extension tubes. The combined 2x2 camera overlap yielded a 13.5 x 21.2 inch (344 x 539 mm) field of view. The PIV image data and laser timing were controlled via an in-house package called PIVACQ, which displayed the acquired camera images in a 2x2-image display on the data acquisition computer. Each camera had a field of view of 7.6 x 11.4inch (193x290 mm). A black velvet-lined shadow box was placed opposite the cameras to provide a dark background in the PIV images and prevent ambient daylight from illuminating the background. To measure the jet plume, the optical equipment was traversed axially to overlapping stations and sampled independently at each station. Seven axial stations were measured at 12-inch (304.8 mm) intervals, yielding a total measurement field of 85.2inches (2.16m), or just over 14 nozzle diameters.

The PIV image data were processed using 64x64 pixel subregions on a 32x32 pixel grid for the first pass and then using six passes (simulated annealing) at 32x32 pixel resolution on a 16x16 grid, and two final passes using subregion distortion processing with 32x32 pixel subregions on a 16x16 pixel grid. The resulting processed velocity grid resolution was 0.047 inch (1.2mm).

When flow statistics are computed from the 400 independent samples at each spatial location, histograms of the velocity values were computed and velocities that lay outside the expected distribution as determined by Chauvenet's criterion were removed from the statistics. When presenting the results below, regions with more than 5% of its points being rejected have their values blanked, a conservative approach to identifying less reliable data. These typically were caused by insufficient seed density in combination with lower light levels at the edges of the laser sheet.

VI. Results

Beyond providing validation data for LES simulations, the test provided insights into how the turbulence energy in the exhaust plume is impacted by changes in the internal mixer and the external plug. This is of interest in current research when trying to understand the changes in noise produced by the variations in flow and geometry. Results are presented below in groups that focus on three issues in aeroacoustics of jets: the difference in turbulence between dual-stream plumes with various degrees of forced mixing, the impact of an external plug on the flow field, and the effect of flight on these plumes.

In the figures below, the flow field for each configuration is given by plots of time-averaged axial velocity U and an approximate turbulent kinetic energy TKE. Only axial u and radial v components of the velocity were measured. However, in previous work [11] it has been observed that the radial and transverse components of turbulent velocity in jets are nearly matched (the radial is roughly 20% smaller than the azimuthal), and thus the quantity

$$TKE = \frac{1}{2}\left(\overline{(u')^2} + 2\overline{(v')^2}\right)$$

is used here as a reasonable approximation for the true definition of turbulent kinetic energy

$$TKE = \frac{1}{2}\left(\overline{(u')^2} + \overline{(v')^2} + \overline{(w')^2}\right),$$

where $\overline{(u')^2} = \frac{1}{T}\int_0^T (u(t) - U)^2 dt$.

A. Structural changes in plumes of dual-stream jets with degree of internal mixing

The objective of a forced mixer, such as the lobed mixer tested here, is to produce a fully mixed plume from the nozzle exit. Doing so with minimal internal losses will produce a thrust benefit and is thought to produce the lowest jet noise. The axisymmetric splitter and lobed mixer configurations, operating at setpoint 3200, represent varying degrees of internal mixing from none to nearly complete. The axisymmetric splitter configuration, operating at the single-stream setpoint 4200, represent the case of a perfect mixer running setpoint 3200. These three flows are shown in Figure 2. Note that the fully expanded velocity of the core and bypass streams was 535m/s and 322m/s, respectively. Their fully mixed velocity was 362m/s. It is of interest to note that while the transverse extent of the flow above say 400m/s is visually reduced by the lobed mixer relative to the axisymmetric splitter, the axial extent is not. In fact, the portion of the plume where velocity is greater than 200m/s is quite a bit longer (both lobed mixer and fully mixed cases) than the unmixed case (axisymmetric splitter).

Referring to Figure 2, the dramatic difference in *TKE* between the axisymmetric splitter and the lobed mixer is shown by the comparing the upper two plots in the figure. Both axisymmetric and lobed mixer configurations have a peak located near the end of their potential cores, but the *TKE* in the lobed mixer plume is reduced to 60% of that in the plume of the axisymmetric splitter. The peak location has also been shifted downstream, corresponding to the lengthening of the plume by the lobed mixer. It is not surprising that the *TKE* a few nozzle diameters downstream of the nozzle is less with the lobed mixer configuration as the outermost flow at the nozzle exit has the velocity of the bypass stream, as opposed to the higher velocity of the fully mixed setpoint (see Figure 2 bottom right). The *TKE* of the fully mixed plume has similar peak *TKE* levels as the lobed mixer flow, but produces this level of *TKE* over most of the axial extent shown here.

It seems noteworthy that the peak *TKE* in the unmixed flow is confined axially to a relatively small axial extent, while the peak *TKE* in the fully mixed flow is relatively uniform over a long axial region roughly corresponding to the potential core of the jet. The flow from the forced mixer is somewhere in between, with more uniform TKE down the shear layer, but a distinctly higher value near the end of the potential core.

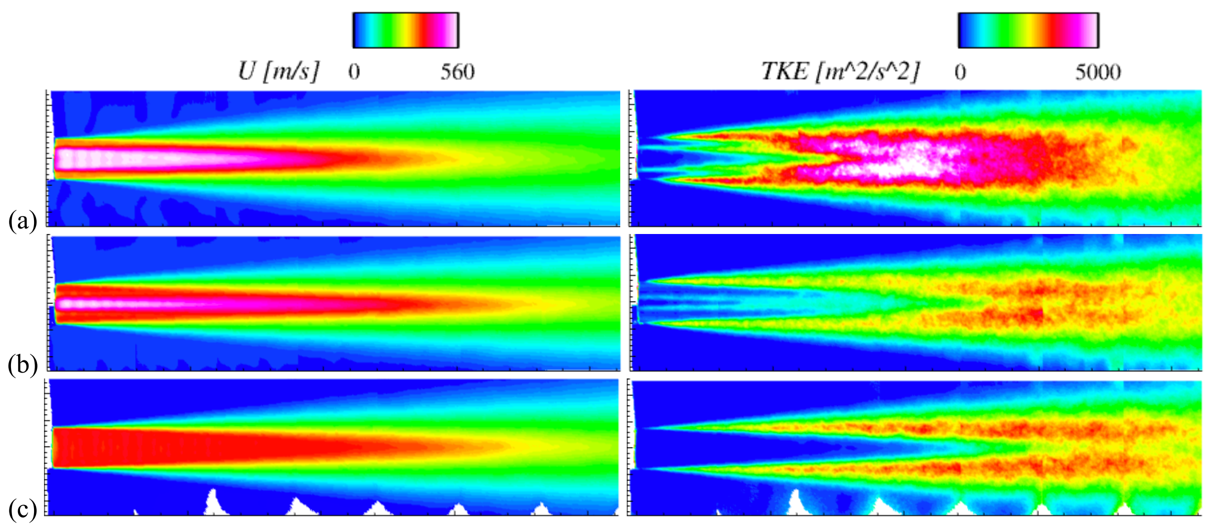


Figure 2 Mean axial velocity and *TKE* for (a) axisymmetric splitter, setpoint 3200, (b) lobed mixer, setpoint 3200, (c) axisymmetric splitter, setpoint 4200 (fully mixed single stream).

B. Effect of external plug

In the acoustic testing we previously reported the noise of a single-stream plume was minimally affected (a little less than 1dB) by the presence of an external plug, at least for plug lengths up to twice the nozzle diameter. However, other researchers have reported reduction in mixing noise for long plugs. Perhaps the most direct measure of the impact of the plug on the plume is to look at setpoint 70, an unheated single-stream plume without a flight stream. Figure 3 presents the mean and *TKE* measurements for a reference simple nozzle with no plug, and two plugs of different length, *p2069* and *p2079*. The exit plane of the nozzles are all aligned in the plots, the external plug blocking the laser light sheet above the plug producing a large blank space.

As noted above, the external plugs suffered droop, even without heat, which caused the tip of the plug to not align with the center of the potential core. In spite of the asymmetry of the plug, the TKE profiles are very nearly the same on both sides of the jet. Also evident upon study is that the mean velocity of the potential core is slightly reduced in the case of the external plug nozzles. Most interesting is that the TKE levels are indeed reduced by the presence of an external plug, consistent with a reduction in noise production at its source. It is postulated that the larger outer radius of the plume caused by having the same nozzle area with and without the plug causes faster mixing and hence decay of the potential core.

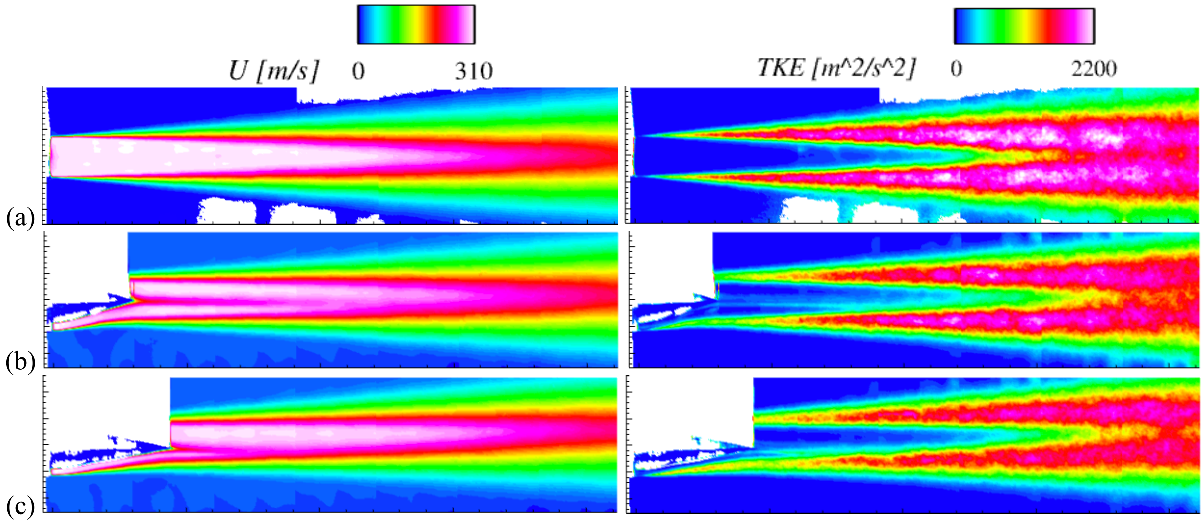


Figure 3 Mean axial velocity and *TKE* for single-stream, unheated (*Ma*=0.9, *Mf*=0) plume from (a) internal plug, (b) short external plug (*p2069*), (c) long external plug (*p2079*). Setpoint 70.

C. Effect of flight stream on single-stream plume

Turning next to how flight streams impact the plume, Figure 4 presents the simple case of an unheated single-stream subsonic jet with flight stream Mach numbers Mf = 0, 0.1, 0.2, and 0.3. From the mean velocity plots we see that the flight stream stretches the potential core of the plume as expected. The blanked regions in the surrounding freejet for the $Mf = 0$ case are indicative of the difficulty in obtaining consistent PIV seed in what is effectively static ambient air.

The turbulence plots in Figure 4 are presented as $TKE/(Uj\text{-}Uf)^2$, where Uf is the velocity of the flight stream. The peak values are expected to be the same in each plot and they nearly are. Note: for the shear layers at $x/D < 1$ the spatial resolution of the PIV causes spatial averaging and reduces the values for turbulent velocities.

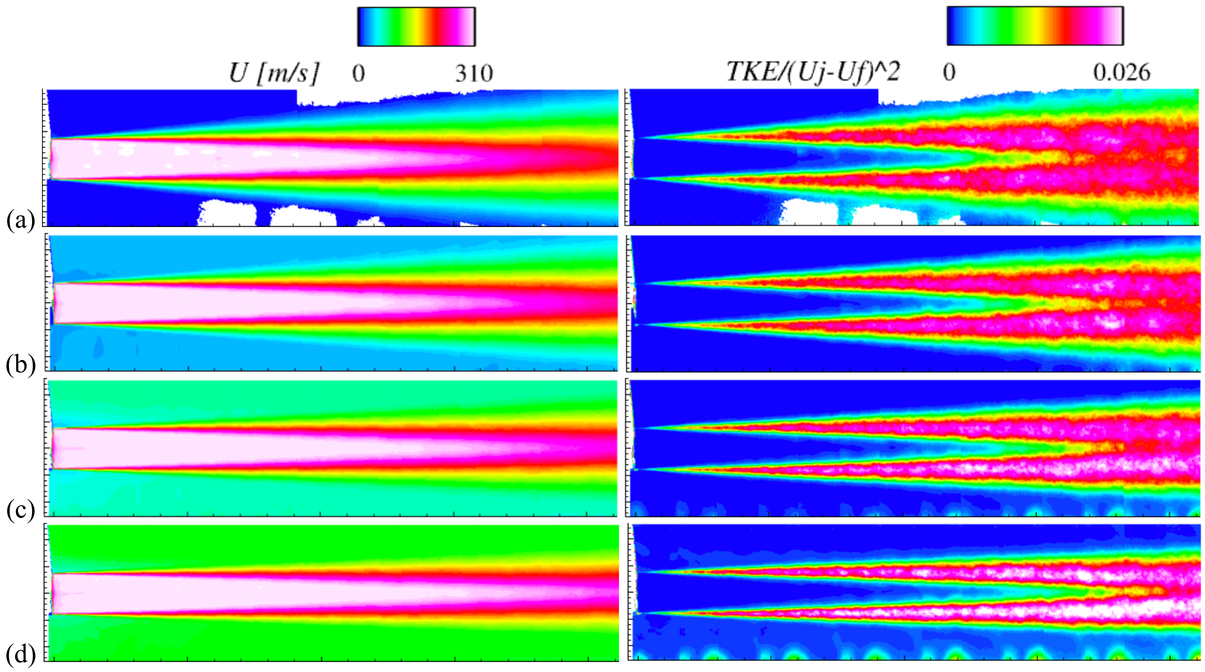


Figure 4 Mean axial velocity and *TKE* for single-stream, unheated (*Ma*=0.9) plume with varying flight streams: (a) *Mf*=0.0, (b) *Mf*=0.1, (c) *Mf*=0.2, (d) *Mf*=0.3.

D. Effect of flight stream on turbulence of unmixed, partially mixed, and fully mixed plumes.

Returning to the comparison of plumes with varying degrees of mixing (Figure 2), we now examine how a dual-stream plume with different degrees of mixing is impacted by being in a flight stream, (Figure 5 and Figure 6). These two figures show a slightly different flow condition from those in Figure 2. Setpoint 1200 is a dual-stream flow condition but unlike setpoint 3200 has a warm fan stream and is more representative of a real engine flow conditions.

Figure 5 compares the plumes of the axisymmetric splitter configuration with and without a flight stream at *Mf* =0.3. Figure 5 shows how the potential core of the axisymmetric splitter/internal plug nozzle is stretched by the flight stream, much like the single-stream jet in Figure 4. And as expected, the amplitude of the TKE is lowered by the reduced shear with flight, although not by as much as the single-stream jet's TKE was. Also, the location of the peak TKE is essentially unchanged by the flight stream. This is unexpected, as the location of the peak TKE is usually associated with the end of the potential core. But the turbulence produced by the strong inner shear layer from the axisymmetric splitter is shielded from the flight stream and it is this shear layer that constitutes the potential core that is more resilient to the flight stream.

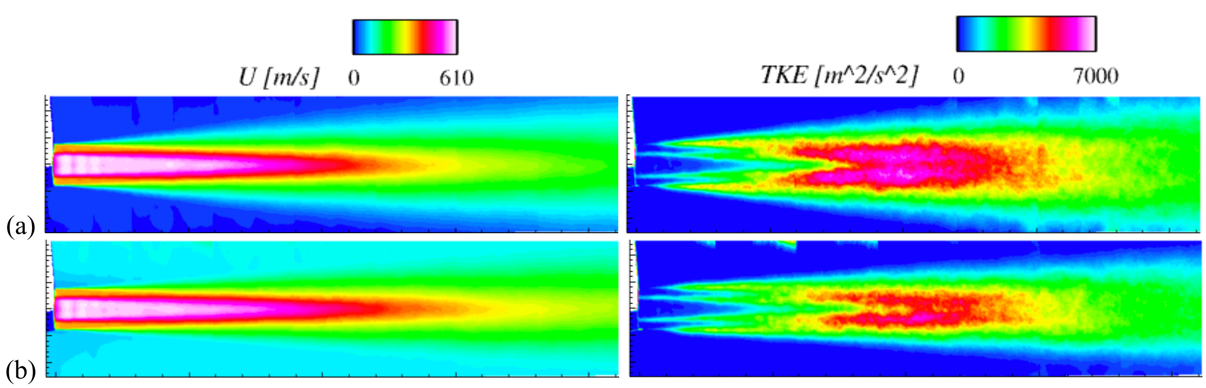


Figure 5 Axisymmetric splitter, internal plug, setpoints 1200/1203 with (a) *Mf* = 0, (b) *Mf* = 0.3.

Figure 6 shows the same flow conditions as Figure 5 but with the lobed mixer in place of the axisymmetric splitter. The lobed mixer produces a plume much more like the single-stream jet, with greater shift in potential core length and a corresponding shift in the location of the peak turbulence. The reduction in TKE is more like that of the single-stream jet.

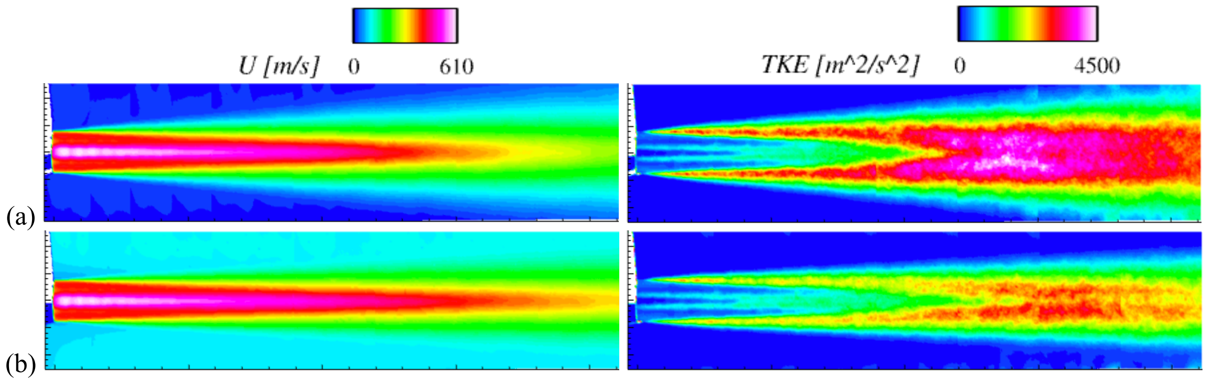


Figure 6 Lobed mixer, internal plug, setpoints 1200/1203 with (a) $Mf = 0$, (b) $Mf = 0.3$.

Finally, Figure 7 shows the same flow conditions and internal mixer as above, but with the external plug in place. A feature of the external plug nozzle is the shock that appears on the crown of the plug just downstream of the nozzle exit. This shock, which appears even at subcritical pressure ratios, is from the curvature of the flow over the plug, and serves to reduce the velocity downstream of the shock. This causes the mean velocity in the plume of an external plug nozzle to be lower, and TKE of the plume to also be reduced. As the flow is now exiting the nozzle at a larger radius, there is more impact from changes in the flight stream. The overall result is a jet with lower TKE than if it emanated from a nozzle without the external plug. Also notable in the plots of mean velocity is the significant asymmetry produced by the droop of the plug, which dislocated the plug by 4% of the nozzle diameter, or 33% of the anulus. Details of this asymmetry will be given in a NASA report, including hot shapes obtained through photogrammetry. For now, note that although the mean flow is very asymmetric, the TKE fields are not. This is in striking contrast to separate flow nozzles where small asymmetries in the nozzle concentricity result in large asymmetries of the turbulence.

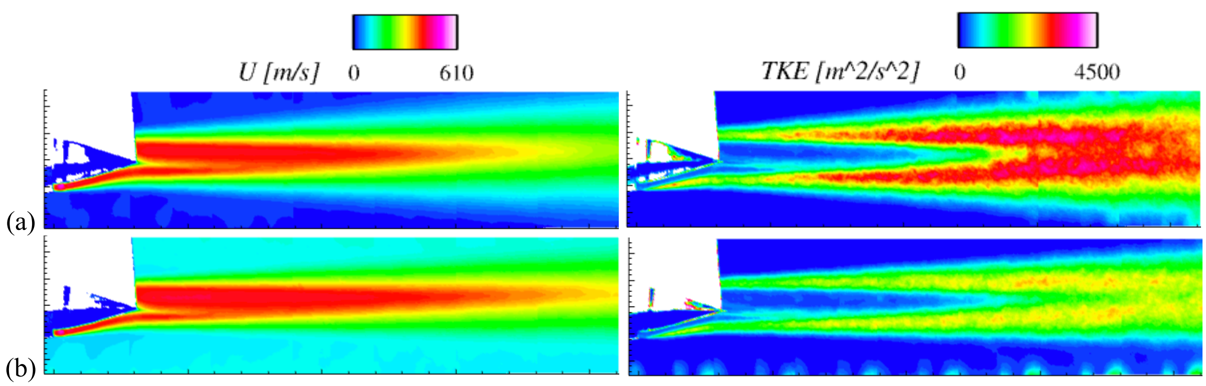


Figure 7 Lobed mixer, short external plug (*p2069*), setpoints 1200/1203 with (a) $Mf = 0$, (b) $Mf = 0.3$.

For completeness, Figure 8 shows the same dual-stream flow coming from the lobed mixer with the long external plug. The results are similar to the short external plug flows, but with the asymmetry even more pronounced. The drooped plug caused the plume to be directed upward, nearly leaving the PIV field of view.

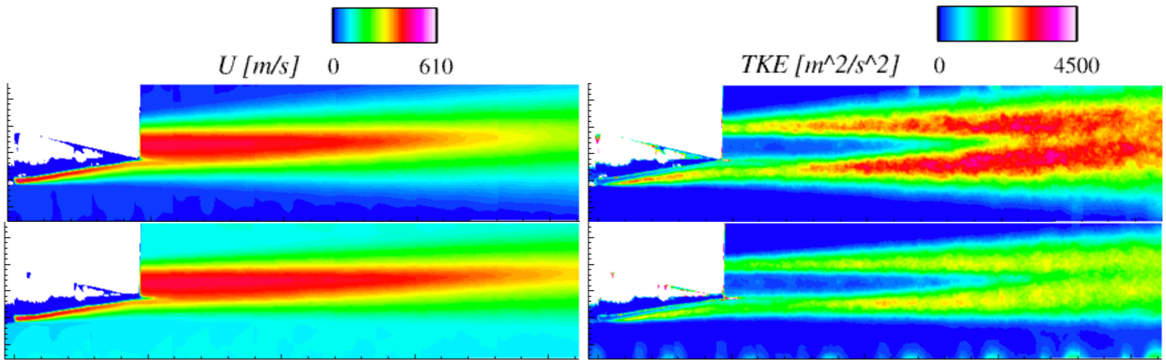


Figure 8 Lobed mixer, long external plug (*p2079*), setpoints 1200/1203 with (a) *Mf* = 0, (b) *Mf* = 0.3.

VII. Summary

The flow fields of plumes from exhaust systems representing those of an internally mixed, moderate bypass ratio turbofan engine are presented. The flow conditions were chosen to be representative of the highest power conditions that commercial supersonic aircraft are likely to be using during takeoff. Other flow conditions were also tested to compare single- and dual-stream plumes with the same fully mixed conditions and hence thrust. Exhaust systems measured had axisymmetric and lobed internal mixers, and internal and external plugs of different length. The effect of the internal mixers was documented, demonstrating the strong impact on plume turbulence, and therefore jet mixing noise, made by having a forced internal mixer. The smaller, but significant impact of an external plug was likewise shown for both single-stream and dual stream flows. The shock on the plug near the nozzle exit, resulting from acceleration of the flow over the crown curvature, dropped the velocity of the jet and thus its turbulence levels. This plug shock is found even in subcritical flows; some reduction in jet velocity and turbulence should be expected in all nozzles with external plugs depending upon local curvature of the plug profile and nozzle pressure ratio. In addition, the impact of a flight stream on the plume turbulence was documented for the various configurations and flow conditions. Generally speaking, the flight stream stretched the plume and reduced the amplitude of the turbulence, although the flow from the axisymmetric splitter had a reduced impact of the flight stream and the location of the peak turbulence was not shifted.

Acknowledgements

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