



Exit Boundary Layer Data for a Round Convergent Nozzle in Support of Numerical Simulation Efforts

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Abstract

An experiment is conducted with hot-wire anemometry to document the exit boundary layer characteristics of two nozzle configurations at jet Mach numbers up to 0.82. Far-field noise and jet plume experimental data from these two configurations have been used in Large Eddy Simulations (LES) of jets by colleagues at other Institutions. The current experiment provides the boundary layer data which have been identified as being critical for validation of the simulations since the initial conditions can significantly affect subsequent jet evolution and its radiated noise. The data exhibit fully turbulent boundary layers for the case with a pipe attached upstream of the nozzle. The case without the pipe involves ‘Blasius-like’ mean velocity profiles but a ‘highly disturbed laminar state’ with large turbulence intensities in a range of subsonic Mach numbers.

Introduction

A round convergent nozzle, designated as ‘SMC000’ (Small Metal Chevron nozzle, baseline case), has been used in investigations of noise and flowfield characteristics of isolated jets as well as various complex flow configurations (Refs. 1 to 3). Some of these experimental configurations, involving either free jets or jet-surface interaction, have recently been explored numerically using Large Eddy Simulation (LES) codes at the Naval Research Laboratory (Code JNRE; Ref. 4) as well as at the NASA Ames Research Center (Code LAVA; Ref. 5). The nozzle has also been used in many other computational efforts at Universities and Industry (e.g., Refs. 6 to 8). The LAVA simulation (Ref. 5) and the corresponding experiment involved a long pipe added upstream of the nozzle (Ref. 3). The simulation in Reference 4, on the other hand, involved usual installation of the nozzle with a convergent adapter attached to the jet facility. The exit boundary layer characteristics of the nozzle with and without the upstream pipe have not been measured in detail before. Since exit boundary layer state and characteristics are known to affect jet evolution as well as its radiated noise (Ref. 9), an effort to document those characteristics was deemed worthwhile. This is carried out in this experiment and the results are presented in the following. The aim is to aid the aforementioned ongoing simulations (Refs. 4 and 5), as well as other future numerical studies, in correctly capturing and validating the initial conditions at the nozzle exit.

Experimental Procedure

All data are acquired in the ‘CW17’ open jet facility at the NASA Glenn Research Center (GRC) (Ref. 9). A picture is shown in Figure 1(a). Compressed air passes through a 30 in. diameter plenum chamber and through the nozzle to discharge into the quiescent ambient of the laboratory. The SMC000 nozzle with and without the upstream pipe is shown in Figures 1(b) and (c), respectively, while a close-up picture of the single hot-wire at the nozzle exit is shown in Figure 1(d). The two nozzle configurations

will be referred to in the following simply as “SMC+” and “SMC”, respectively. The nozzle has a 2 in. exit diameter. The upstream pipe is 12 in. long with a 2.25 in. internal diameter.

Computer Aided Design (CAD) files of the two nozzle configurations, and all experimental results in digital format, can be found on a supplemental CD. It should be noted that the CAD files for the nozzle include an upstream adapter used in experiments in the Aeroacoustic Propulsion Laboratory (AAPL) (Refs. 1 to 3); in the CW17 facility a different adapter had to be used. However, the contraction ratio is large in each case; starting from 6 in. diameter in the AAPL case and starting from 5.16 in. diameter in the CW17 case. Thus, the difference is thought to have negligible effect in the boundary layer characteristics at the exit of the 2 in. diameter nozzle. The SMC nozzle is convergent with a 5° half angle at the exit. Note that the upstream pipe is only slightly larger than the 2 in. exit and thus the turbulent boundary layer developed over the 12 in. length of the pipe persists through the nozzle, as will be seen in the results presented in the following.

Boundary layer (BL) measurements are done using the hot-wire technique using a Thermo Systems Inc. anemometer (TSI, IFA100). A TSI-1260-10A miniature probe is used—a close-up view of the probe placed just downstream of the nozzle can be seen in Figure 1(d). The hot-wire sensor diameter and active length are 0.001 and 0.01 in., respectively; the prong-to-prong distance of the sensor is about 0.040 in. Most of the measurements are made about 0.040 in. downstream of the nozzle exit. The probe is inserted at an angle (about 45° to the flow direction) and only the sensor wire and the prongs enter the flow. In some experiments profiles are taken 0.025 in. from the nozzle, as far upstream as possible without risking breakage (there was a slight shudder of the probe when taking steps during the measurements). In one case, the probe was placed at a point on the high-speed edge of the BL just upstream of the exit ($x \approx -0.005$ in.) to document the velocity spectra there; the purpose is explained later with the data.

A personal computer based data acquisition system with ‘Labview’ software is used for the measurements. All data presented in the following pertain to subsonic, unheated flow; i.e., with total temperature the same throughout as in the ambient of the test chamber. The ‘jet Mach number’,

$M_j = (((p_0 / p_a)^{(\gamma-1)/\gamma} - 1) \frac{2}{\gamma-1})^{1/2}$, is used in the following as the independent variable; here, p_0 and p_a are

plenum pressure and ambient pressure, respectively. Data are presented up to M_j of about 0.82, the corresponding Reynolds number based on the diameter is 1.12×10^6 . Note that the jet Mach number is different from ‘acoustic Mach number’, defined as $M_a = U_j / c_a$, where U_j is the fully expanded jet velocity and c_a is the speed of sound in the ambient air.

Electronic noise, a 22 kHz peak and its harmonics, occurred in the hot-wire signal that could not be eliminated in limited trials. The consequence was that the turbulence measured within the core of the jet was higher than the expected value of less than 0.5 percent. It was decided to move forward with the measurements since this had no perceptible effect on the boundary layer profiles where the turbulence was much higher; (the velocity profiles and their integral characteristics for known cases matched with previous measurements when there was no electronic noise). Also it should be noted that the hot-wire measurements in the low-speed ‘tail’ regions of the profiles are contaminated by large flow angularity due to high turbulence (relative to the local mean velocity). The profiles beyond the 20 percent core velocity point involve errors and are qualitative. Care was taken to ensure good repeatability of the data; mean velocities within the core of the jet were repeatable within 1 percent. In all profile calculations the data were normalized by the measured mean velocity in the core of the jet.

Apart from the electronic noise and sensor survivability concerns, there are other issues in hot-wire measurements in high-speed compressible flows. In this flow regime, the hot-wire responds to the product of density and velocity rather than just velocity as in incompressible flows. With constant temperature anemometer operation the sensitivity to temperature is thought to be small. The probe is calibrated at the

nozzle exit against the jet velocity U_j calculated from the plenum pressure. In the measurements, a probe voltage is converted to velocity and then nondimensionalized by the jet velocity U_j . Since the probe actually responds to ρu , approximately $\rho U/\rho_j U_j$ is measured for the ‘mean velocity’ and $(\rho u)'/\rho_j U_j$ is measured for the ‘turbulence intensity’. In view of the measurement difficulties and ambiguities, the profiles and thickness estimates should be considered as qualitative at high values of M_j . They are, however, considered adequate to capture the overall characteristics of the boundary layer and differentiate between laminar and turbulent states.

Results

For the results, the BL integral characteristics are shown first in order to focus attention on the salient differences between the data for the SMC and the SMC+ configurations. This is followed by detailed profiles to illustrate the sources of the differences. The momentum thickness (δ_2) variation with M_j is shown in Figure 2. Throughout the M_j -range, δ_2 is much smaller for the SMC case measuring as little as 0.002 in. and as high as 0.004 in. on the high end of the M_j -range covered. The value of δ_2 for the SMC+ nozzle is high throughout and at least three times larger than the values for the SMC nozzle. Corresponding peak turbulence intensity data are presented in Figure 3. One notes that the levels are low for the SMC+ case but the SMC case exhibits large values within the M_j range of 0.33 to 0.55. The high turbulence is indicative of a ‘disturbed laminar state’.

In Reference 9 similar measurements were reported for a host of 2 in. diameter nozzles; an interested reader may find a discussion of the boundary layer states in that reference as well as earlier publications cited therein (e.g., Ref. 10). Thus, a ‘turbulent’ state involves usual decay of the mean velocity over a long distance until dropping sharply near the wall. The entire boundary layer involves turbulent fluctuations. However, a common experience is that peak turbulence intensity is often much lower for a nozzle flow than that seen in a zero-pressure gradient flat-plate boundary layer; (5 to 7 percent as opposed to about 10 percent). A ‘nominally laminar’ state involves a thin BL where the mean velocity profile is similar to the classic ‘Blasius’ shape, however, the turbulence is non-zero and often can be large (larger than that seen with a turbulent BL). Sometimes the ‘nominally laminar’ state can involve very large turbulence intensity (say, 12 percent or higher); this is designated as the ‘highly disturbed laminar’ state. It is clear that the SMC nozzle involves the highly disturbed laminar state over a narrow range of M_j (≈ 0.33 to 0.55). This is in contrast to previous observations (Ref. 9) where a given state persisted with a given nozzle throughout the subsonic range (up to $M_j \approx 1$). Thus, the highly disturbed laminar state was observed with two ASME nozzles (‘design’ and ‘long’). On the other hand, a nominally laminar state was found with a short ASME nozzle while a turbulent state occurred for a conic nozzle.

From the data of Figure 3, one may be tempted to conclude that the SMC nozzle BL goes through a transition, becoming highly disturbed laminar in the M_j range of 0.33 to 0.55 but settles back to a turbulent state around $M_j = 0.6$. That this notion is incorrect becomes apparent from the velocity profiles discussed next.

Velocity profiles are shown in Figures 4 and 5 corresponding to two M_j -locations in Figure 3, one near the peak turbulence at $M_j = 0.43$ and another at $M_j \approx 0.76$ (corresponding to acoustic Mach number $M_a = 0.70$). The peak turbulence is about the same for the two configurations at the latter Mach number. While the peak turbulence is about the same, it is seen from Figure 4 that the mean velocity profiles are vastly different. For the SMC+ case (Fig. 4(b)) the mean velocity decay starts at a much smaller radius. (Data had to be taken up to $r = 0.62$ in. to reach a ‘plateau’. The abscissa scales are chosen for easy comparison yet showing the profiles as clearly as possible). Note also that throughout the r -range covered higher turbulence persists for the SMC+ case. Estimated shape factor (δ_1/δ_2) is about 1.5, and clearly this

configuration involves a fully turbulent boundary layer. (δ_1 is the estimated displacement thickness; this is not shown further since errors involved in its calculation is large compared to that in δ_2 , due to measurement errors in the tails of the mean velocity profiles). Comparatively, with the SMC case (Fig. 4(a)) the U -profile plateaus to a value of unity within a short range of r from the wall exhibiting a much thinner boundary layer. Estimate of the shape factor (δ_1/δ_2) turns out to be close to 2 in this case. This is a ‘nominally laminar’ BL; the mean velocity profile is not too different from the ‘Blasius profile’ but there is significant turbulence. This state, observed with some other nozzles, e.g., a short ASME case (Ref. 9), may be differentiated from the ‘highly disturbed laminar’ state where the turbulence intensities are very large.

Corresponding profiles for the two nozzle configurations at $M_j = 0.43$ are compared in Figure 5. The large turbulence peak for the SMC case is conspicuous and the boundary layer is very thin. This is the ‘highly disturbed laminar’ state. One finds that the highest intensity occurs on the lower speed side where $\rho U/\rho_j U_j$ is about 0.27. Corresponding data for the SMC+ case $M_j \approx 0.43$ (Fig. 5(b)) exhibit a fully turbulent state and the profiles are similar to those seen at the higher M_j (Fig. 4(b)). The turbulence intensity profile for the latter case appears somewhat different with slightly larger amplitudes.

Sample time traces of the hot-wire signal are shown in Figures 6 and 7, corresponding to the cases of Figures 4 and 5. In each figure, the top trace corresponds to a location on the high-speed edge of the BL (about 98 percent velocity point) whereas the bottom trace corresponds to a location where the turbulence intensity profile has its peak. The traces are recorded at a rate of 20 kHz and thus the abscissa spans 0.75 secs. Corresponding digital data files, attached with the electronic version of this TM, have the full records spanning about 5 secs. The SMC and SMC+ cases exhibit comparable peak turbulence intensities at the higher M_j of 0.76 (Fig. 4); the amplitudes in Figure 6(b) for the SMC+ case (shown without normalization) are larger simply because U_j is higher. At $M_j = 0.43$ (Fig. 7), the signals exhibit large negative skewness. While the signal at the maximum intensity point for the SMC+ case is turbulent with smaller amplitudes (Fig. 7(b)), very large fluctuations occur for the SMC case leading to the conspicuous peak in Figure 5(a). Spectra of the velocity signals are briefly discussed at the end.

The near exit streamwise evolution of the velocity profiles are captured in Figure 8 for $M_j = 0.76$ and in Figure 9 for $M_j = 0.43$. In each figure the top row shows mean velocity profiles, and turbulence intensity profiles are shown in the bottom row. These measurements cover a streamwise distance of 0.025 to 0.64 in. from the nozzle exit. In Figure 8(a), a thin initial shear layer is indicated for the SMC case while Figure 8(b) exhibit a wider shear layer for the SMC+ case; note the difference in abscissa scales. The turbulence intensity profiles (Figs. 8(c) and (d)) exhibit comparable amplitudes with difference in width commensurate with the mean velocity profiles. Corresponding data at $M_j = 0.43$ (Fig. 9) exhibit similar evolution for the two configurations, as seen in Figure 8, with one significant exception. The intensities are very large near the nozzle exit for the SMC case. However, the amplitudes for both configurations become comparable farther downstream past $x = 0.16$ in.

Salient features of near exit streamwise variations of U and u' profiles are summarized in Figures 10 and 11. The momentum thickness variations with x are shown in Figure 10 while the variations of peak turbulence intensity are shown in Figure 11. The data trends discussed already with previous figures are captured succinctly in these two figures. The momentum thickness is larger for the SMC+ case and the difference with the SMC case persists over the measurement range. The high turbulence for the SMC case at the lower M_j subsides within a short distance from the nozzle exit and only a slightly higher level persists farther downstream.

Finally, a set of spectra of the hot-wire signal are shown in Figure 12 to make some observations. The raw (nonlinearized) signals are analyzed for convenience. The signals are low-pass filtered appropriately and the spectra are obtained over 0 to 25 kHz using the same data acquisition (Labview) program used for

the profile measurements. Because of nonlinearity of the hot-wire signal the spectra shown are not true power spectra of the velocity fluctuations but they are nonetheless adequate for making the following observations. The three spectra in Figure 12 are for indicated (x, r) locations. The blue curve is from the high-speed edge of the BL at $x = 0.040$ in. where the turbulence is relatively low (corresponds to upper velocity trace in Figure 7(a)). The red curve corresponds also to the high-speed edge but from a location just upstream of the nozzle exit (this is as far upstream as the probe could be placed yet clearing the nozzle exit, Figure 1). The peaks around 22 kHz due to electronic noise mentioned earlier are visible in both these spectra. The green curve corresponds to data at the peak turbulence location at $x = 0.040$ in. (corresponds to the lower velocity trace in Figure 7(a)). First, one notes that there are no conspicuous peak in any of the spectra. Thus, there is no organized periodic fluctuations in the flow. The question came up if the large turbulent fluctuations seen for $M_j = 0.43$ originated from upstream or occurred after the boundary layer relaxed into the free shear layer. The almost identical blue and red traces clearly suggest that the fluctuations must have originated upstream.

Concluding Remarks

As stated earlier, it is hoped that these boundary layer data will be useful in numerical simulations. It is apparent that the SMC+ case has a fully turbulent exit BL. This is a well-defined predictable state and thus might be easier for the simulations. However, in the experiments it was a special case where the upstream pipe was added due to facility constraints, (so that the exit of the jet could be placed at a certain location relative to an adjacent surface (Ref. 3)). The SMC case is the common geometry that has been used in many experiments. Unfortunately, the exit BL for this case is Mach number dependent. It should be noted that the highly disturbed laminar state, occurring for this case in the M_j range 0.33 to 0.55, is not uncommon and characterizes other nozzle geometries, e.g., the ASME cases discussed in Reference 9. Numerically, it might be a challenge to capture this state. On the other hand, it might be an interesting case for a study of transition with nozzle boundary layers. For LES studies with the SMC nozzle it may be best, if possible, to avoid the aforementioned Mach number range.

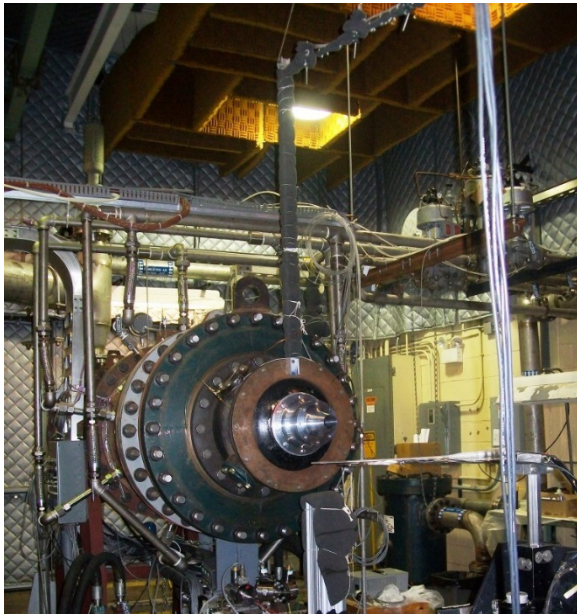
Appendix—Supplemental CD

Supplemental digital data for all figures is available in an accompanying CD (available online from www.sti.nasa.gov) for those interested in further analysis. Following are brief descriptions of those digital data.

- CAD Files: the nozzle geometries and the adapter with and without the upstream pipe are given in two file formats.
- Figures 2 and 3: The file “BL_survey_log_organized” contains the data. Here ‘d2’ = momentum thickness (δ_2), ‘umx’ = peak turbulence intensity in the BL and ‘M’ = M_j .
- Figures 4 and 5: There are four data files where, ‘y’ = r , ‘ub’ = $\rho U/\rho_j U_j$ and ‘ur’ = $\rho u'/\rho_j U_j$.
- Figures 6 and 7: The time trace data are taken at 20 kHz rate and about 5 secs of data are recorded for each case. Note that the signals recorded are unfiltered.
- Figures 8 and 9: In each of the four cases, data for six x -stations are given. The variable names are the same as in the file ‘Figures 4 and 5’. For Figures 8(a) (c), use ‘composite-altered’ data set; (the r -axis for $x = 0.32$ and 0.64 in the raw data sets are off by 0.026 in.)
- Figures 10 and 11: The BL integral data are given and the variables are the same as in the file ‘Figures 2 and 3’.
- Figure 12: Raw hot-wire signal spectra are given and the (x, r) locations associated with each curve can be found from the zone headers.

References

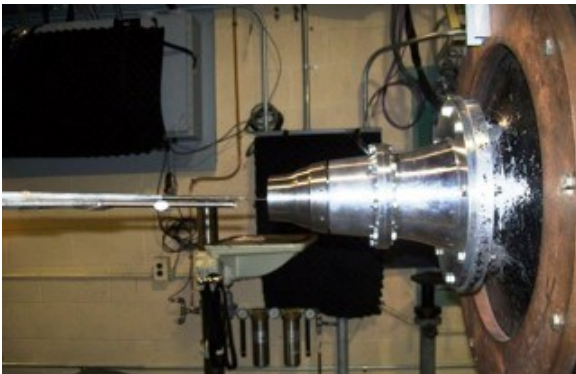
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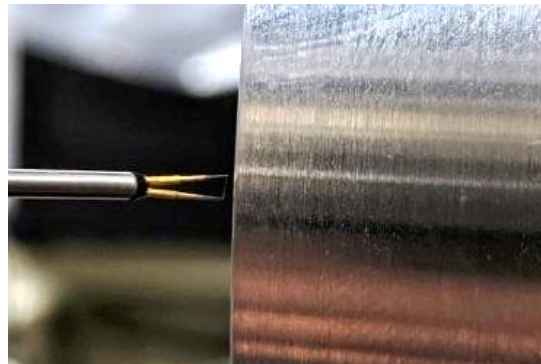
(a)



(b)



(c)



(d)

Figure 1.—Experimental facility. (a) Open jet rig, (b) SMC000 nozzle with 12 in. long upstream pipe, (c) SMC000 nozzle without upstream pipe, (d) close-up view of single hot-wire at nozzle exit.

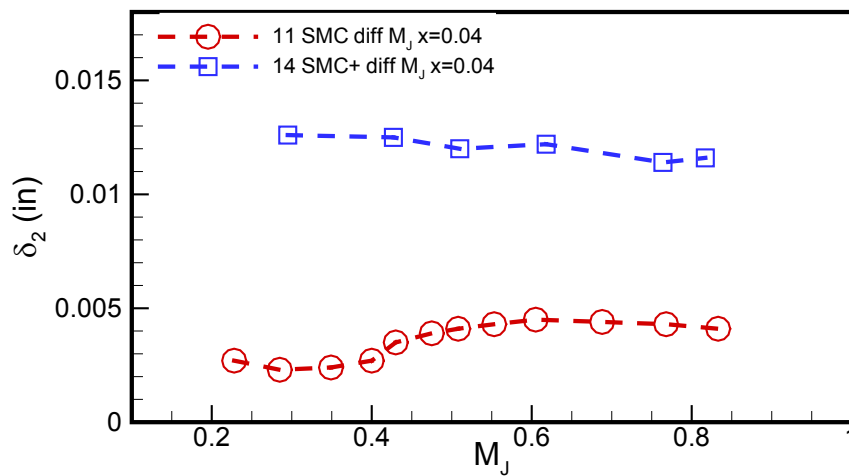


Figure 2.—Boundary layer momentum thickness vs. M_j , measured 0.040 in. downstream from nozzle exit. “SMC+” denotes SMC000 nozzle with upstream pipe.

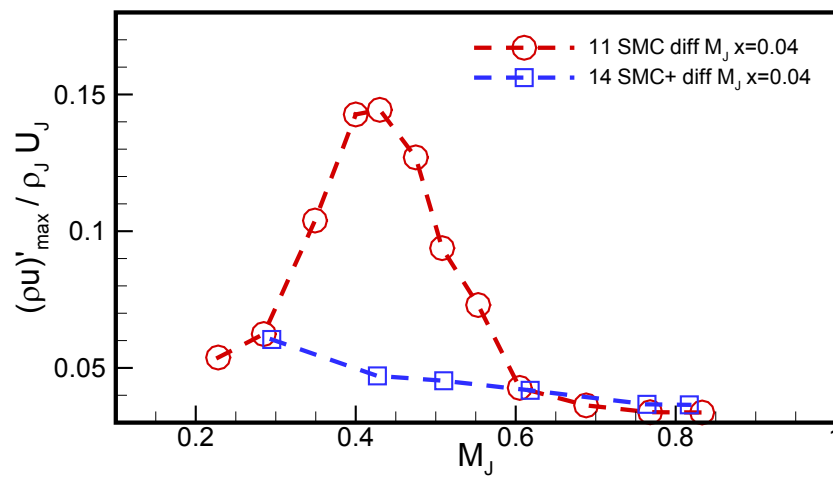


Figure 3.—Maximum turbulence intensity in the exit boundary layer vs. M_j , corresponding to the data of Figure 2.

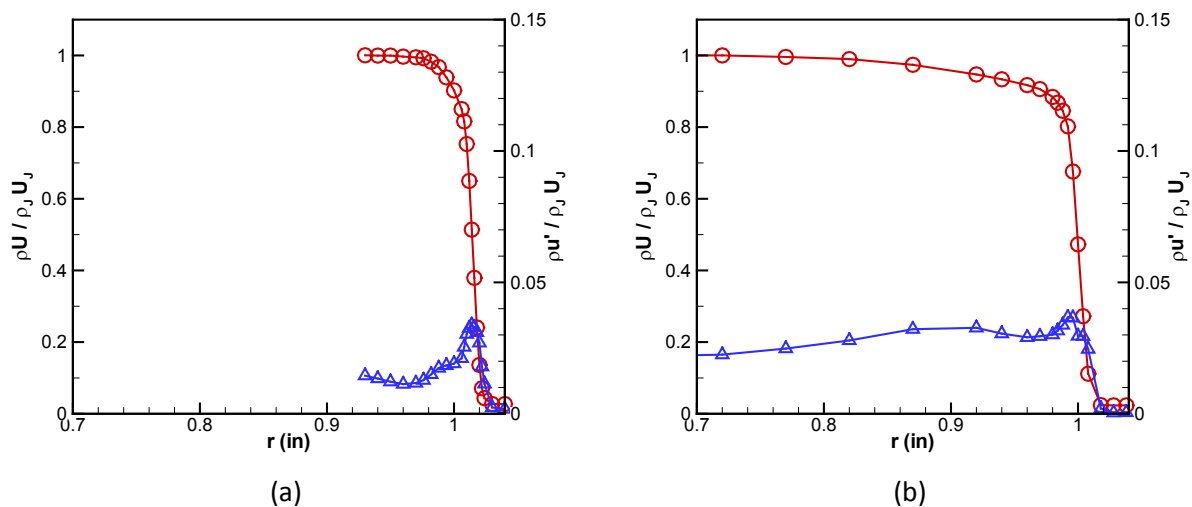


Figure 4.—Mean velocity (red, circles) and turbulence intensity profiles (blue triangles). (a) SMC, $M_j = 0.768$, (b) SMC+, $M_j = 0.764$.

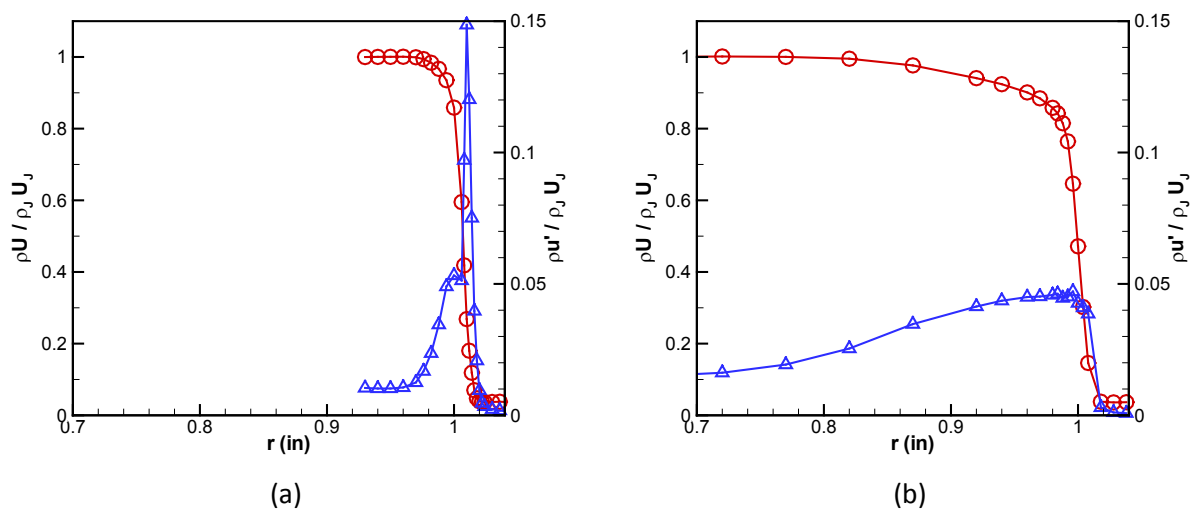
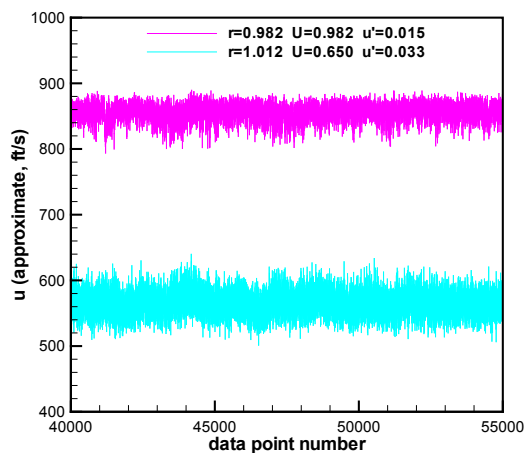
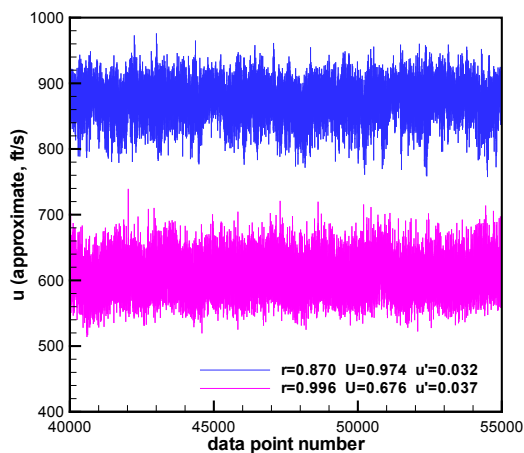


Figure 5.—Radial profiles of mean velocity (red, circles) and turbulence intensity (blue triangles). (a) SMC, $M_j = 0.426$, (b) SMC+, $M_j = 0.427$.

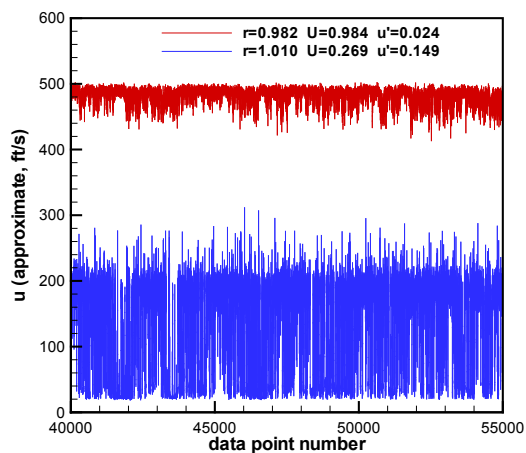


(a)

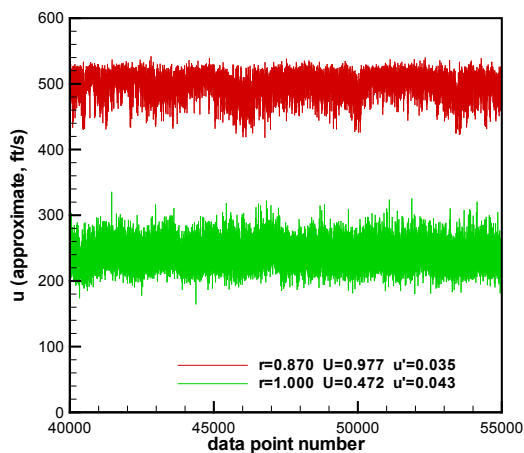


(b)

Figure 6.—Sample velocity signals in the boundary layer at $M_j \approx 0.76$. (a) SMC, (b) SMC+; in each figure the top trace is at the high-speed edge of the boundary layer while the bottom trace is at maximum velocity point. In the legend, radius r in inches, $U = \rho U / \rho U_j$ and $u' = \rho u' / \rho U_j$.



(a)



(b)

Figure 7.—Sample velocity signals in the boundary layer at $M_j \approx 0.43$ shown similarly as in Figure 6. (a) SMC, (b) SMC+.

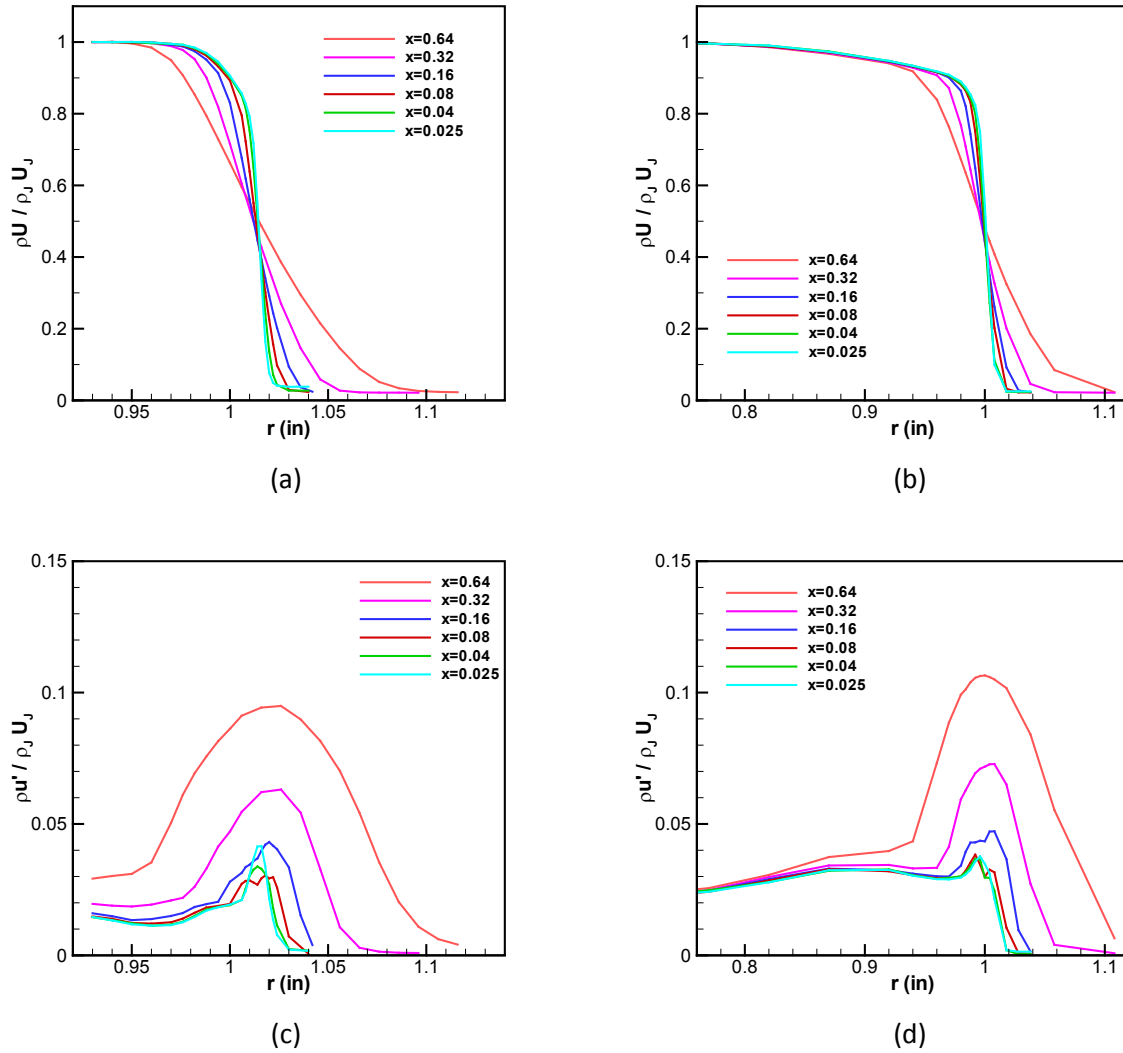
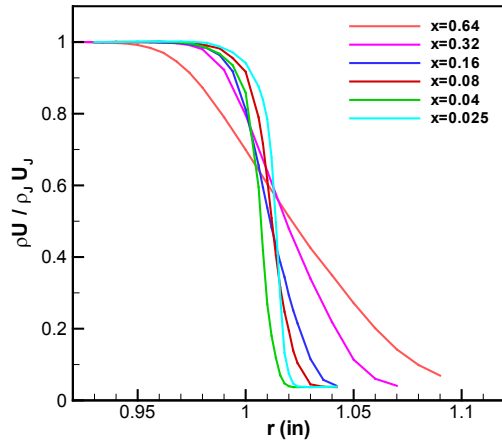
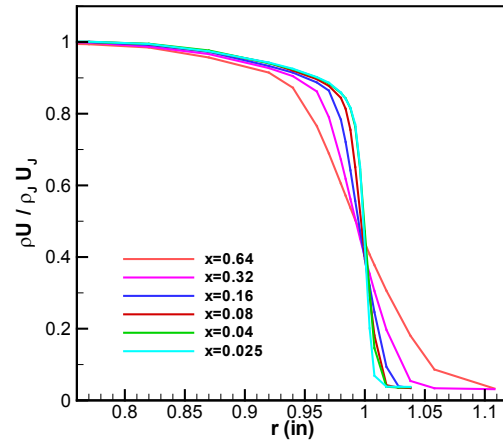


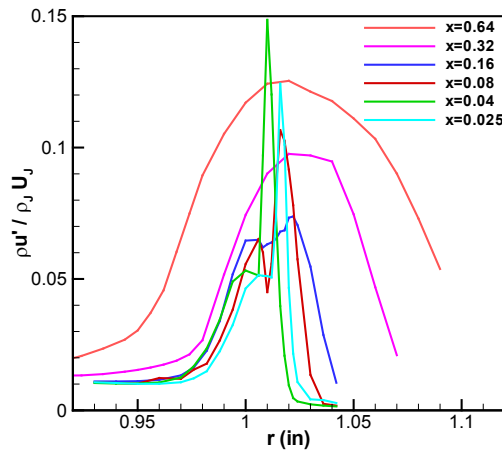
Figure 8.—Evolution of velocity profiles close to the nozzle exit at $M_j \approx 0.76$. Top row: Mean velocity profiles at indicated x -locations (inches); bottom row: corresponding turbulence intensity profiles. Left column: SMC case, right column: SMC+ case.



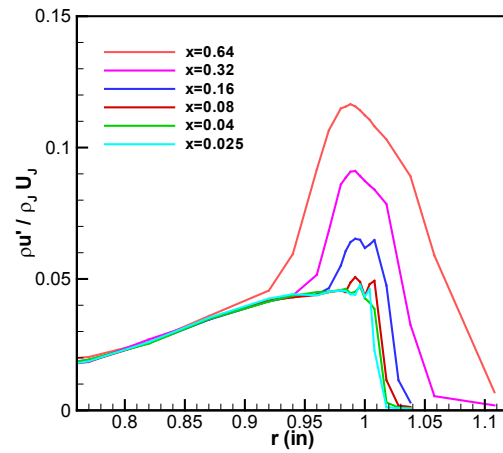
(a)



(b)



(c)



(d)

Figure 9.—Evolution of velocity profiles close to the nozzle exit at $M_j \approx 0.43$. Mean velocity profiles (top row) and turbulence profiles (bottom row), for SMC (left column) and SMC+ case (right column), shown similarly as in Figure 8.

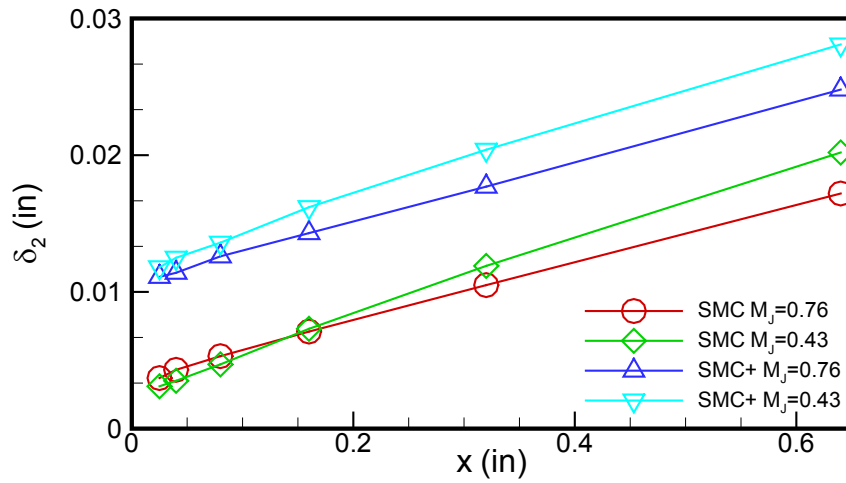


Figure 10.—Boundary layer momentum thickness evolution with streamwise distance x .

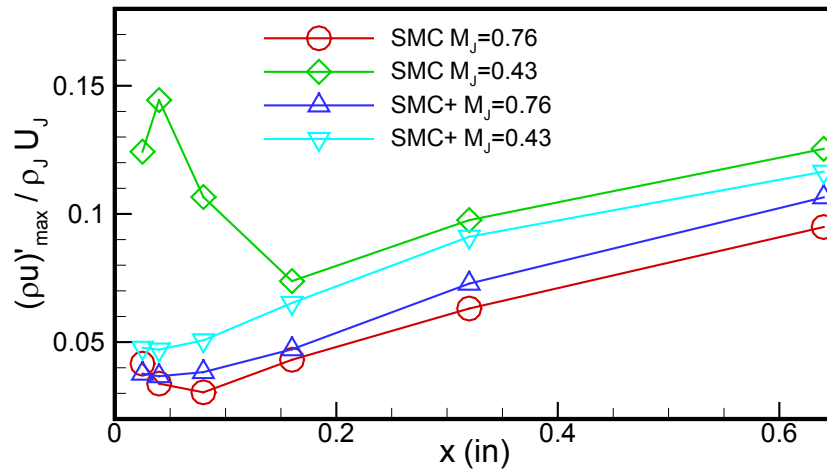


Figure 11.—Maximum turbulence intensity evolution with x corresponding to the data of Figure 10.

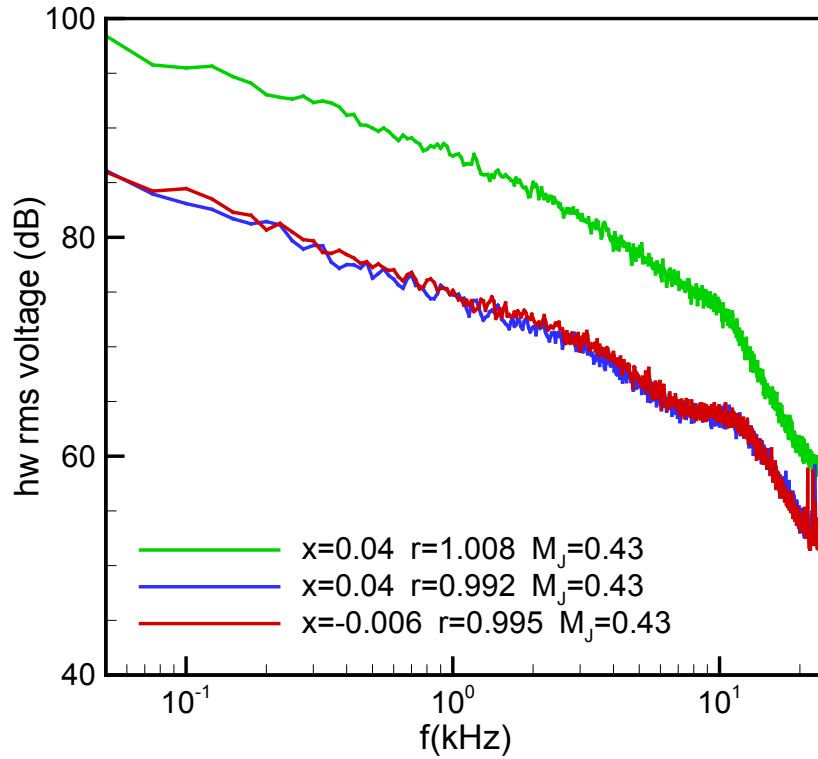


Figure 12.—Spectra of raw hot-wire signal in the boundary layer for the SMC case at $M_j = 0.43$. Green: at peak turbulence point, blue: at high-speed edge, red: at high-speed edge but just upstream of nozzle exit. In the legend, x and r are in inches.

