AIAA 2001-0668

Experiments on Mixing Enhancement in Dual-Stream Jets

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39th AIAA Aerospace Sciences Meeting & Exhibit
8-11 January 2001 / Reno, NV
Flow exiting a convergent-divergent nozzle operated at off-design conditions exhibits an instability that causes mixing enhancement in the flow itself and can destabilize an adjacent flow. The latter property enables mixing enhancement of an arbitrary jet via parallel injection of a secondary gas flow. In this study we extend the method of mixing enhancement using secondary parallel injection (MESPI) to high-aspect ratio rectangular (2D) jets and obtain data on flow structure and scalar mixing for both 2D and axisymmetric jets. The turbulent structure is visualized using spark schlieren photography and planar laser induced fluorescence (PLIF). The rate of mixing is described by centerline velocity distributions, obtained by pilot surveys, and concentration measurements, obtained by time-averaged PLIF. The MESPI jet is compared to a reference jet with equal mass flow rate and equal momentum flux. The mixing diagnostics show that MESPI halves the length of the potential core in both round and 2D jets. A short distance past the potential core, mixing enhancement causes a reduction in centerline Mach number of 30% in round jets and 20% in 2D jets. The corresponding reduction in the peak molar concentration of a scalar injected in the primary flow is 65% in round jets and around 40% in 2D jets.

Introduction

The plume of a shock-containing, convergent-divergent nozzle exhibits strong unsteadiness which causes mixing enhancement in the plume itself and can enhance mixing of an arbitrary flow adjacent to the plume. This phenomenon was discovered in coannular jet experiments at U.C. Irvine [1] and was subsequently confirmed in large-scale tests at NASA Glenn Research Center [2]. The method of Mixing Enhancement via Secondary Parallel Injection (MESPI) is characterized by the simplicity of the mixer nozzles, so it is relevant to combustion and propulsion applications. This study extends the previous works to high-aspect ratio rectangular (2D) nozzles pertinent to applications such as low-observable aeroengines. In addition, we study the flow structure and scalar mixing of axisymmetric and 2D configurations.

Figure 1 shows the generic geometry of the MESPI nozzle and of the reference nozzle against which the performance of the MESPI nozzle is judged. The primary (inner) flow is the same in both cases; its conditions are irrelevant to the instability mechanism. The secondary (outer) flows of the MESPI and reference nozzles are subjected to the same pressure ratio; they have equal mass flow rates and, to within a few percent, same thrust. For the MESPI nozzle, the duct of the secondary flow is convergent-divergent with exit-to-throat area ratio $A_e/A_s$. Mixing enhancement occurs when the secondary flow reaches sonic speed at the throat and experiences an adverse pressure gradient near the nozzle exit. The secondary-flow duct of the reference nozzle is convergent. Previous work has shown that mixing enhancement overlaps with the expected occurrence of supersonic nozzle flow separation [1]. For $A_e/A_s = 1.35$ (the value used in this study) flow separation, and consequently mixing enhancement, occurs for nozzle pressure ratios in the range 1.3-3.0, approximately. The physical mechanisms of MESPI remain

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unknown and are presently under investigation. Aeroaoustic resonance – a phenomenon similar to screech in imperfectly-expanded supersonic jets – has been largely ruled out as the root cause of MESPI [2].

If one wishes to include the single jet (primary flow alone) in the comparisons of mixing performance, it is possible to do so by defining a mass-flow-rate-equivalent diameter

$$D_m = D_1 \sqrt{\frac{m_1 + m_2}{m_1}}$$

where subscripts 1 and 2 refer to the primary flow and secondary flows, respectively, and $D$ is the diameter of the primary flow (for the rectangular jet, this should be the equivalent area-based diameter $D_{eq,1}$ of the primary flow). Normalization of the axial coordinate by $D_m$ scales all the jets to the same mass flow rate. One should keep in mind that the fluid dynamics of the single jet and of the dual-stream jet are very different, even in the absence of MESPI. There is no way for a simple transformation like this to make the two flows totally equivalent. Moreover, the equal-mass-flow-rate scaling holds only in the near field of the jet. In the very far field, a thrust-based diameter makes more sense since the jet is reduced to a point force. However, most mixing enhancement applications are concerned with the near field.

**Diagnostics**

It was desired to obtain qualitative images of the turbulent structure and quantitative information on mixing and its enhancement. To this end we used schlieren photography, pitot pressure measurements along the centerline of the jet, and planar laser induced fluorescence in instantaneous and time-averaged modes. The schlieren system employed a 20-nanosecond spark for light source (Xenon, Model N787), lenses with 150-mm diameter and 1-m focal length for collimating the beam, and a charge coupled device (CCD) camera for collecting the image (Photometrics, Star I). The pitot probe had a flattened inlet $0.2 \times 2.0$ mm and was connected to a pressure transducer (Setra, Model 280).

The arrangements for PLIF imaging are sketched in Fig. 4. The seed molecule was gaseous acetone injected into the primary flow. Ultraviolet light from a pulsed Nd:Yag laser (Continuum, Surelite II) was formed into a sheet which sliced the flow either in the $y-z$ plane or the $x-y$ plane and excited the acetone molecules, which fluoresced in the visible range. Instantaneous images were collected by an intensified CCD camera (Princeton Instruments ICCD 576/RB). Time-averaged (mean) images were collected by the Photometrics Star 1 CCD camera. For the mean images, the camera shutter was open for 10 seconds, collecting the fluorescence excited by 100 laser pulses. In other words, each mean image is an ensemble average of one hundred instantaneous images. Because a small amount of stray light was collected in the mean images, a background image (acquired with the laser on the flow off) was subtracted from the mean image for each
run. Mean imaging was done only in the $y-z$ plane; as seen later, it provides quantitative information on mixing. Instantaneous imaging was done in both $y-z$ and $x-y$ planes. Slices in the $y-z$ plane were obtained at several streamwise locations using small axial increments near the jet exit and larger steps past the potential core of the jet. Slices in the $x-y$ plane were obtained at two adjacent downstream locations, each slice occupying an axial extent of 100 mm. For all experiments, the laser pulse energy was 40 mJ. For the mean PLIF, the mole fraction of acetone was 1.9% in the round jets and 1.6% in the rectangular jets. For instantaneous imaging, the acetone mole fraction was around 3%.

**Flow Conditions**

Table 1 summarizes the flow conditions. For the axisymmetric tests, comparisons were made between the single (primary) jet (AXI-0), the primary jet surrounded by secondary flow from a convergent nozzle (AXI-C) and the primary jet surrounded by secondary flow from a convergent-divergent nozzle (AXI-CD). The same type of comparison was done for the rectangular jets (2D-O/0, 2D-C/C, 2D-CD/CD), including cases where the secondary flow came from one side only (2D-C/0, 2D-CD/0). All the secondary CD nozzles had exit-to-throat area ratio $A_e/A_t = 1.35$.

**Schlieren Photography**

Figure 5 presents schlieren images of three axisymmetric cases, all sharing the same Mach 1.5 primary flow. Depicted are the single jet (AXI-0) in Fig. 5(a); the jet surrounded by secondary flow from a convergent nozzle (AXI-C) in Fig. 5(b); and the jet surrounded by secondary flow from a convergent-divergent nozzle (AXI-CD) in Fig. 5(c). Application of the coflow from a convergent nozzle, Fig. 5(b), stabilized the jet as expected from the reduced velocity difference across the jet's shear layer. The coflow from the convergent-divergent nozzle had the opposite effect and destabilized the jet. Figure 6 makes a similar comparison for the rectangular cases 2D-O/0, 2D-C/C, and 2D-CD/CD. As in the round cases, the convergent secondary flow stabilizes the jet while the convergent-divergent secondary flow destabilizes it. Figure 7 compares 2D jets with secondary flow supplied on one side only. Again, the converging secondary flow (2D-C/0) reduces mixing while the convergent-divergent secondary flow (2D-CD/0) enhances it.

**Centerline Mach Number Distributions**

A quantitative measure of mixing enhancement is the decay of centerline Mach number with axial distance. A faster decay indicates stronger mixing between the primary flow and the ambient fluid. The centerline Mach number distribution also defines the length of the potential core. Figure 8 shows centerline Mach number distributions for the axisymmetric cases AXI-0, AXI-C, and AXI-CD. In Fig. 8(a), the Mach number is plotted against $x/D_1$. On this basis, one can make direct comparisons between AXI-C and AXI-CD since they have same mass flow rate and same thrust. Strictly speaking, AXI-0 should not be part of the comparison because it has smaller mass flow rate and smaller thrust; it is included here for completeness. It is evident that the potential core of AXI-CD is roughly one half that of AXI-C: switching the nozzle of the secondary flow from convergent to convergent-divergent resulted in a shortening of the potential core from $x/D_1 = 8$ to $x/D_1 = 4$. At $x/D_1 = 10$ the centerline Mach number of AXI-CD is 30% lower than that of AXI-C and 22% lower than that of AXI-0. The three axisymmetric flows are compared on an equal-mass-flow rate basis in Fig. 8(b), where the Mach number is plotted against $x/D_m$. The distributions of AXI-0 and AXI-C nearly coincide, which lends some credence to the $D_m$ scaling. On this basis, the MESSI jet (AXI-CD) has the same benefit against the single jet (AXI-0) and the reference jet (AXI-C).

Figure 9 makes analogous comparisons for the rectangular jets 2D-O/0, 2D-C/C, and 2D-CD/CD. In terms of equivalent diameter $D_{eq,1}$ the 2D single jet has a much shorter potential core than the axisymmetric single jet: $x/D_{eq,1} \approx 2.5$ versus $x/D_1 \approx 6$. This is expected since the potential core should scale with the minor dimension of the nozzle, in this case the exit height $h = 6.35 \text{ mm} = 0.32D_{eq,1}$. In terms of $x/h$, the potential core of the 2D jet is close to that of the round jet. For practical applications, however, we should use an equal-exit-area (or equal mass flow rate) basis. Proceeding now to the coflowing cases, Fig. 9(a) shows that 2D-C/C elongates the potential core to $x/D_{eq,1} \approx 3.8$ while 2D-CD/CD shortens it to $x/D_{eq,1} \approx 1.8$, roughly a 50% reduction. The Mach number distribution of 2D-C/C is a little jagged which indicates the presence of shocks in the plume. We suspect that they are caused by compression of the inner flow by the outer flow due to the slightly inward direction of the outer streams. This effect is noticeable in the 2D-C/C case but largely absent in the 2D-CD/CD case, whose outer flow has less of an inward direction. At $x/D_{eq,1} = 4$ the centerline Mach number of 2D-CD/CD is 18% lower than
Table 1  Jet conditions

<table>
<thead>
<tr>
<th>CASE</th>
<th>Primary flow</th>
<th>Secondary flow</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_1$</td>
<td>$U_1$</td>
<td>$D_1$</td>
</tr>
<tr>
<td>AXI-0</td>
<td>1.50</td>
<td>430</td>
<td>12.7</td>
</tr>
<tr>
<td>AXI-C</td>
<td>1.50</td>
<td>430</td>
<td>12.7</td>
</tr>
<tr>
<td>AXI-CD</td>
<td>1.50</td>
<td>430</td>
<td>12.7</td>
</tr>
<tr>
<td>2D-0/0</td>
<td>1.50</td>
<td>430</td>
<td>20.1</td>
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<td>2D-C/C</td>
<td>1.50</td>
<td>430</td>
<td>20.1</td>
</tr>
<tr>
<td>2D-CD/CD</td>
<td>1.50</td>
<td>430</td>
<td>20.1</td>
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<tr>
<td>2D-C/0</td>
<td>1.50</td>
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<tr>
<td>2D-CD/0</td>
<td>1.50</td>
<td>430</td>
<td>20.1</td>
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</tbody>
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$D_1$ is $D_{eq,1}$ for 2D jets

$M$ is ideally-expanded Mach number

For axisymmetric jet, $Re_1$ is based on primary diameter $D_1$.

For 2D jet and for all secondary flows, $Re$ is based on jet height.

$F$ is thrust based on ideal expansion

that of 2D-C/C and 12\% lower than that of 2D-0/0. On an equal-mass-flow-rate scaling, Fig. 9(b), the distributions of 2D-0/0 and 2D-C/C coincide and the MESPI jet has same benefit against either the single jet or the reference jet.

Figure 10 compares the centerline Mach number distributions of rectangular jets 2D-0/0, 2D-C/0, and 2D-CD/0. On an equal-mass-flow-rate basis, the plots of the single and reference jets coincide in the near field and deviate slightly for $x/D_m > 10$. The plot of 2D-CD/0 is less jagged than that of 2D-CD/CD in Fig. 9, indicating a milder compression effect. Interestingly, the MESPI jet with secondary flow on one side only (2D-CD/0) performs equally well as the MESPI jet with secondary flow on both sides (2D-CD/CD in Fig. 9), even though its secondary mass flow rate is one half that of 2D-CD/CD. This hints that asymmetric nozzle arrangements hold promise for further destabilization of the flow.

Instantaneous PLIF Images

$x - y$ sections

Figures 11 through 13 depict instantaneous $x - y$ slices of the axisymmetric and 2D jets of this study. For each jet, a composite of two time-uncorrelated images is shown. The images of AXI-0, AXI-C and AXI-CD in Figure 11 capture the same trends seen in the schlieren images of Fig. 5: stabilization of the jet with application of secondary flow from convergent nozzle and destabilization when the secondary flow is supplied from a CD nozzle. The AXI-CD jet mixes much faster than the AXI-C jet and moderately faster than the AXI-0 case. The 2D jet images of Figs. 12 and 13 reveal something not easily discernible in the schlieren images, that is, a flapping motion present in all jets. The instability is suppressed in cases 2D-C/C and 2D-C/0 and is enhanced in cases 2D-CD/CD and 2D-CD/0.

$y - z$ sections

The evolution of the streamwise turbulent structure of cases AXI-C and AXI-CD is summarized in Fig. 14. The images are scaled to their respective maximum and minimum intensities (“autoscaled”), hence do not capture the decline of concentration, hence fluorescence signal, with downstream distance. At $x/D_1 = 3$, AXI-C retains a near-circular shape but AXI-CD shows signs of instability. This difference is amplified at $x/D_1 = 6$ where the jet column of AXI-C maintains its integrity while that of AXI-CD is substantially deformed. Further downstream, at $x/D_1 = 12$ and 16, the enhanced mixing and instability of AXI-CD is evident. Similar comparisons for the rectangular jets are offered in Fig. 15 which compares 2D-C/C with 2D-CD/CD, and in Fig. 16, which compares 2D-C/0 with 2D-CD/0. For both sets of comparisons, instability of the MESPI flows is evident as early as $x/D_{eq,1} = 1.9$ and becomes full-fledged at $x/D_{eq,1} = 3.2$ and beyond. Notable is the ejection of primary fluid towards the secondary-flow side of 2D-CD/0 at $x/D_{eq,1} = 4.4$.

Mean PLIF Images

An often-used measure of mixing is the spatial distribution of the mean concentration of a scalar seeded in the flow. The scalar here is the gaseous acetone in-
jected in the primary flow. One can study how the concentration profiles spread and, most importantly, how the peak concentration declines with axial distance. The experiments presented here compare the mean concentration fields of the MESP1 jet, the reference jet, and the single jet in axisymmetric and 2D nozzles. For each set of comparisons, the acetone mass fraction and laser energy were kept constant. A progression of $y-z$ slices provided the fluorescent intensity distribution $\bar{I}(x_n, y, z)$ at discrete axial locations $x_n$. If the laser sheet were perfectly uniform, then $\bar{I}(x_n, y, z)$ would be directly proportional to the local mean mole fraction of acetone, $\varepsilon(x_n, y, z)$. The laser beam is gaussian, however, so its distribution is not uniform. In the present arrangement, Fig. 4(a), the light intensity is fairly uniform in $y$ but gaussian in $z$. If the laser sheet spreads out enough, and if its center passes through the centerline of the jet (where the maximum concentration levels are expected), then the light intensity is practically uniform in an area surrounding the center of the jet, i.e.

$$\bar{I}(x_n, y, z) = k\varepsilon(x_n, y, z), \quad |z| < Z_0/2$$

where $k$ is a constant and in our case $Z_0 \approx 50$ mm. Note that $\varepsilon$ is not a conserved scalar. This is proportional not only to the local mass fraction of acetone (which is a conserved scalar) but also on the local density of the flow. Hence, flow compression increases the fluorescence signal and expansion reduces it.

Figure 17 compares mean PLIF images of AXI-C and AXI-CD at the several axial locations. The images are autoscaled so the streamwise reduction in intensity is not captured. The faster spreading rate of AXI-CD is evident. The same type of comparison is done in Fig. 18 for the rectangular cases 2D-C/C and 2D-CD/CD. Again, the mixing enhancement of the MESP1 jet is obvious. It is also seen that both rectangular jets tend towards circular shape as the axial distance increases. At $x/D_{eq,1} = 6.3$ the MESP1 jet is practically circular but the reference jet is still in transition to circular shape. Similar observations are made in Fig. 19 which compares the rectangular jets 2D-C/0 and 2D-CD/0. Notable is the expulsion of primary fluid towards the unstable part of jet 2D-CD/0, a phenomenon also noted in the instantaneous images of Fig. 16.

From the images exemplified in Figs. 17 through 19, the mean intensity along the jet centerline, $\bar{I}(x_n, 0, 0)$, was computed. The axial distribution of centerline intensity for the axisymmetric jets is plotted in Fig. 20. As in the Mach number plots, comparisons are performed on two bases: equal-primary-area and equal-mass-flow-rate. On the latter basis, Fig. 20(b), the plots of AXI-0 and AXI-C nearly coincide. At $x/D_m = 6$ the intensity from AXI-CD is 40% lower than that of either AXI-C or AXI-0; at $x/D_m = 8.2$, the intensity reduction is 65%. Analogous plots for rectangular jets 2D-0/0, 2D-C/C, and 2D-CD/CD are graphed in Fig. 21. The intensity distribution of 2D-C/C presents an increase in the near field which could be due to the compression effect noted earlier. This may explain why the intensity distributions of 2D-C/C and 2D-0/0 do not collapse well as their Mach-number counterparts in Fig. 9. At $x/D_m = 2.5$ (near the end of the potential core of the reference jet), the intensity of the MESP1 jet is roughly 55% that of the reference jet and 60% that of the single jet. Finally, Fig. 22 shows the centerline intensities for jets 2D-0/0, 2D-C/0, and 2D-CD/0. The intensity of the reference jet (2D-C/0) still has a small spike in the near field, but is less pronounced than in case 2D-C/C. The curves for 2D-0/0 and 2D-C/0 collapse reasonably well when plotted versus $x/D_m$. At $x/D_m = 2.5$, the intensity reductions due to MESP1 are 40% relative to the reference jet and 30% relative to the single jet, i.e., a performance comparable to the symmetric case of Fig. 21.

**Thrust Impact**

A question that inevitably arises in this kind of investigation is the impact of the off-design operation of the CD nozzle of the secondary flow on thrust performance. There is currently little information on the details of supersonic nozzle flow separation, especially in moderate expansion nozzle such as ours. We are not even sure if the separation shocks in our nozzles are of the lambda type or oblique. What we can say with certainty is that one-dimensional theory is inadequate for reliable thrust prediction. Instead, we turn to the scarce experimental thrust data available for this flow, summarized in Fig. 23. Plotted is the actual-to-ideal thrust ratio as a function of nozzle area ratio for nozzle pressure ratio 2.0. A least-squares linear fit gives

$$\frac{F}{F_{ideal}} \approx 1.0 - 0.2 \left( \frac{A}{A_c} - 1 \right)$$

For $A/A_c = 1.35$ the thrust ratio is 0.93, hence the thrust loss for the secondary flow is 7%. This loss should be distributed over the entire jet using the thrust ratio $F_E/F_j$ in Table 1. The overall thrust loss is 1.4% for AXI-CD, 1.7% for 2D-CD/CD, and 0.9% for 2D-CD/0. These numbers appear small compared to the losses incurred by mechanical mixers, which tend to be in the 5-to-10 percentile range for the class of flows examined here [6].
Conclusions

The mixing performance of axisymmetric and two-dimensional MESPI (Mixing Enhancement via Secondary Parallel Injection) jets was assessed using probe and optical measurements. The MESPI jets were compared to reference jets having equal mass flow rate and thrust, and to scaled-up single jets having equal mass flow rate. For all jets, the primary flow was at Mach number 1.5 and velocity of 430 m/s. Instantaneous visualizations using schlieren and PLIF techniques show details of the flow structure and its destabilization when MESPI is applied. The 2D jet, in particular, exhibits a flapping motion which is amplified in the case of MESPI. Centerline Mach number measurements show that MESPI reduces the length of the potential core by 50% in both axisymmetric and 2D jets. A short distance past the end of the potential core of the reference jet, MESPI causes a Mach number reduction of 30% in the axisymmetric jets and 20% in the rectangular jets. At the same general location, the fluorescence signal emitted by gaseous acetone seeded in the primary flow decreased by roughly 65% in the axisymmetric jets and by 40 to 50% in the rectangular jets. Of special interest is the 2D jet with secondary flow on one side only, which is as unstable as its symmetric counterpart.

Acknowledgments

The support by NASA Glenn Research Center is gratefully acknowledged (Grant NAG-3-2345 monitored by Dr. Khairul Zaman).

References


Figure 1: Generic geometry of (a) MESPI nozzle and (b) reference nozzle. The inner streams are identical; the outer streams are supplied at the same pressure ratio and same mass flow rate.

Figure 2: Axisymmetric dual-stream jet facility. In this study, air was supplied to both primary and secondary nozzles.

Figure 3: High-aspect-ratio rectangular (2D) triple-stream jet facility.

Figure 4: PLIF setup for (a) $y-z$ cross sections and (b) $x-y$ cross sections.
Figure 5: Spark schlieren images of jets (a) AXI-0; (b) AXI-C; and (c) AXI-CD.

Figure 6: Spark schlieren images of jets (a) 2D-0/0; (b) 2D-C/C; and (c) 2D-CD/CD.
Figure 7: Spark schlieren images of jets (a) 2D-C/0 and (b) 2D-CD/0.

Figure 8: Centerline Mach number distributions for the axisymmetric jets. Flows are compared (a) on an equal-primary-area basis and (b) on an equal-mass-flow rate basis.
Figure 9: Centerline Mach number distributions for rectangular jets 2D-0/0, 2D-C/C, and 2D-CD/CD. Flows are compared (a) on an equal-primary-area basis and (b) on an equal-mass-flow rate basis.

Figure 10: Centerline Mach number distributions for rectangular jets 2D-0/0, 2D-C/0, and 2D-CD/0. Flows are compared (a) on an equal-primary-area basis and (b) on an equal-mass-flow rate basis.
Figure 11: Instantaneous $x-y$ PLIF images of axisymmetric jets. Field of view spans from $x/D_1 = 0$ to 17.

2D-C/0

Figure 13: Instantaneous $x-y$ PLIF images of rectangular jets 2D-C/0, and 2D-CD/0. Field of view spans from $x/D_{eq,1} = 0$ to 11.

Figure 12: Instantaneous $x-y$ PLIF images of rectangular jets 2D-0/0, 2D-C/C, and 2D-CD/CD. Field of view spans from $x/D_{eq,1} = 0$ to 11.
Figure 14: Streamwise sequence of instantaneous $y - z$ PLIF images of axisymmetric jets AXI-C and AXI-CD.

Figure 15: Streamwise sequence of instantaneous $y - z$ PLIF images of rectangular jets 2D-C/C and 2D-CD/CD.
Figure 16: Streamwise sequence of instantaneous $y - z$ PLIF images of rectangular jets 2D-C/0, and 2D-CD/0.

Figure 17: Streamwise sequence of mean $y - z$ PLIF images of axisymmetric jets AXI-C and AXI-CD.
Figure 18: Streamwise sequence of mean $y-z$ PLIF images of rectangular jets 2D-C/C and 2D-CD/CD.

Figure 19: Streamwise sequence of mean $y-z$ PLIF images of rectangular jets 2D-C/0 and 2D-CD/0.
Figure 20: Centerline fluorescence intensity distributions for axisymmetric jets. Flows are compared (a) on an equal-primary-area basis and (b) on an equal-mass-flow rate basis.

Figure 21: Centerline fluorescence intensity distributions for rectangular jets 2D-0/0, 2D-C/C, and 2D-CD/CD. Flows are compared (a) on an equal-primary-area basis and (b) on an equal-mass-flow rate basis.
Figure 22: Centerline fluorescence intensity distributions for rectangular jets 2D-0/0, 2D-C/0, and 2D-CD/0. Flows are compared (a) on an equal-primary-area basis and (b) on an equal-mass-flow rate basis.

Figure 23: Thrust coefficient versus area ratio for nozzle pressure ratio 2.0. Experimental data are from [3] for $A_r/A_* = 1.2$; [4] for $A_r/A_* = 1.3$; and [5] for $A_r/A_* = 1.8$. Dashed line is least-squares fit. This plot applies to the secondary flow only of the MESPI jets.