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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

This report contains preliminary findings, subject to revision as analysis proceeds.

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Abstract

A numerical study employing a simplified model of the High Speed Civil Transport mixer/ejector nozzle has been conducted to investigate the effect of tabs (vortex generators) on the mixing process. More complete mixing of the primary and secondary flows within the confined ejector lowers peak exit velocity resulting in reduced jet noise. Tabs were modeled as vortex pairs and inserted into the computational model. The location, size, and number of tabs were varied and its effect on the mixing process is presented here both quantitatively and qualitatively. A baseline case (no tabs) along with six other cases involving two different vortex strengths at three different orientations have been computed and analyzed. The case with the highest vorticity (six vortices representing large tabs) gives the best mixing. It is shown that the influence of the vorticity acts primarily in the forward or middle portions of the duct, significantly alters the flow structure, and promotes some mixing in the lateral direction. Unmixed pockets were found at the top and bottom of the lobe, and more clever placement of tabs improved mixing in the vertical direction. The technique of replacing tabs with vortices shows promise as an efficient tool for quickly optimizing tab placement in lobed mixers.

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1. Introduction

DEVELOPMENT of a new generation high-speed civil transport aircraft has become of interest in the past few years. For several years, NASA's High Speed Research (HSR) program had been working on methods to reduce noise at takeoff conditions for the large engines required for these aircraft. The HSR program met its goals of developing an adequate mixer/ejector nozzle, but the resulting nozzle was very long and heavy.

This work expands on efforts of the older HSR noz-

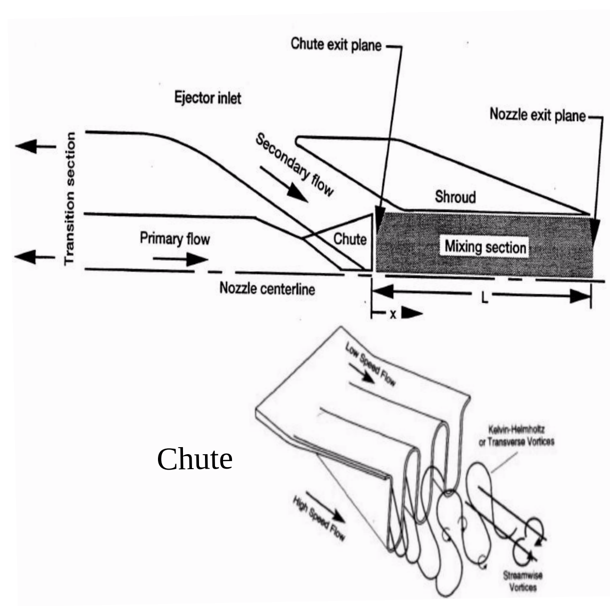

Figure 1: Schematics of mixer/ejector nozzle.[5,15]

zle designs, and looks to improve these by maturing enhanced mixing technology to enable shorter, lighter nozzles.

The mixer/ejector nozzle is designed to reduce noise to below Federal Aviation Regulation (FAR) 36 stage III requirements while maintaining high thrust levels. The mixer/ejector nozzle lowers peak jet speed, and consequently noise, but retains thrust levels due to an increase in the mass flow through the nozzle (Figure 1). In an effort to augment the mixing rate of the primary and secondary streams, and, hence, minimize the required length of the ejector duct, lobed mixers are typically employed to enhance the mixing rate between the two streams. These mixers augment mixing by increasing the interface area between the two streams, and in some cases introducing streamwise and transverse vorticity into the mixing layer[13]. In addition to lobed structures that promote mixing, it has been shown via experimental testing that streamwise vortices generated from mixing enhancement devices on the lobes also help to reduce noise with little impact on thrust levels[6].

Much work has gone into understanding the mixing process and the additional effect of passive devices such as tabs in conjunction with lobed structures. Seiner & Grosch[12] analyzed jet plume mass flow entrainment rates associated with the introduction of counter-rotating streamwise vorticity by tabs located at the lip of nozzle. DeBonis[5] did calculations for multiple lobes without devices and modeled the the nozzle upstream of the lobed mixer as well as the the mixer/ejector itself. Thus, boundary layers were allowed to form before entering the nozzle. Foss & Zaman[6] investigated experimentally the HSCT nozzle with different patterns of tabs, and have quantified the circulation and related it to the size of the tabs.

The intent of this study is to develop a simplified representation of a mixer/ejector nozzle configuration employing multiple lobes with mixing enhancement devices. Nozzles with and without mixing enhancement devices were examined. The gridding complexity of tabbed nozzles with upstream geometry have been replaced by an approximate model where the tabs (mixing enhancement devices) are modeled by pairs of vortices.

A series of calculations has been completed to assess the capability of the CFD code to handle the relevant flowfield with the addition of counter-rotating vortex pairs, representing physical mixing devices placed at the inflow of a rectangular duct. A parametric study was conducted on three different vortex location schemes for two different vortex intensities for the subsonic nozzle mode. The quantified mixing effect of the devices on the two inflow streams was evaluated and compared with the no-vortex baseline solution. This data will provide a strategic starting point for testing of a new 1/7 scale mixer/ejector nozzle with mixing enhancement devices at Glenn Research Center.

2. Approach

A. Problem Description

The current CFD model is based on a 1/7 scale model of the full-scale mixer\ejector nozzle, which contains ten mixer lobes, or chutes, five on the top and five on the bottom. The simplified 3-D CFD model is basically a rectangular duct, and represents one mixing lobe or chute.

The inflow plane of the computational model is composed of two regions as seen in Figure 2 (colored by stagnation temperature), a primary and a secondary, or a

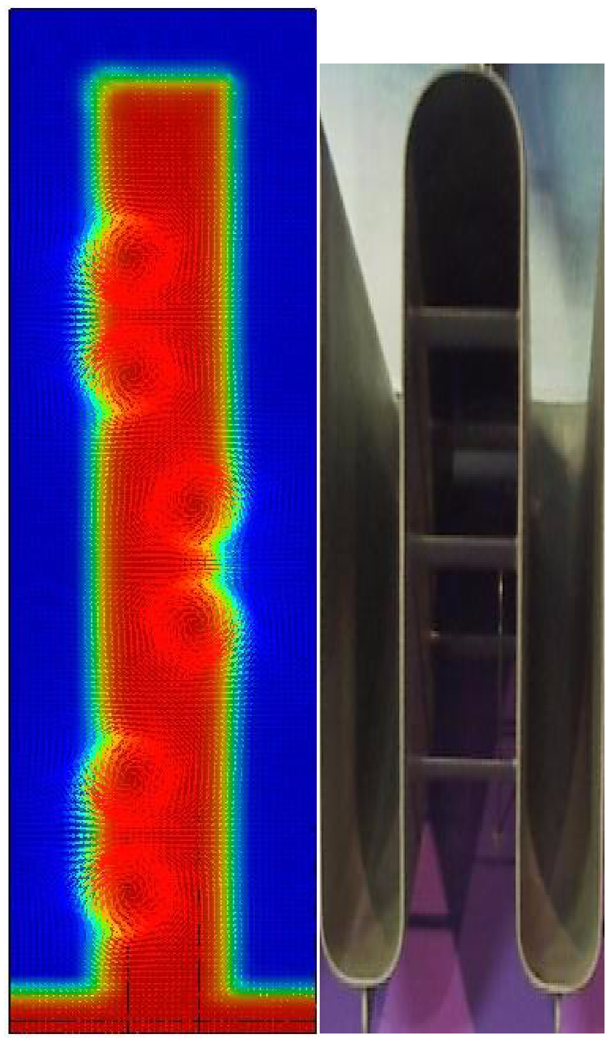

Figure 2: Structure of inflow plane colored by stagnation temperature (left) as produced with the preprocessor. 6 vortices (3 tabs) are also present. Compare with a prototype engine lobe on the right.

hot and cold, sections. The hot section (the lobe) represents flow entering from the engine itself and the cold represents the external subsonic flow being entrained into the nozzle. The mixing region is at a constant cross section. The rounded lobes in the real mixer were replaced with the simpler rectangular lobe. No boundary layers of any type are present at the inflow plane, presenting a difficult starting condition for the CFD solver. Significant convergence issues resulted from the large gradients between the hot and cold sections. A region of smoothly varying flow properties was inserted between the hot and cold regions for the initial iteration. The gradients in this region were applied such that the slopes of the stagnation properties were smooth and continuous across the boundary. This smoothing region can be seen bounding the lobe in Figure 2.

Inflow conditions were chosen to represent the engine exit conditions. Ideal-ejector analysis[10] was used to determine the exact flow conditions, and to insure that the secondary flow did not choke. This analysis was used to predict the equilibrium pressure between the primary and secondary streams, and associated total conditions and Mach numbers of the two incoming streams, based on an assumed exit pressure of 14.3 psi.

The hot section is set to total conditions of 1483 R (824 K), 37.15 psi (756 140 N/m^2), and Mach number 1.44. The cold section is set to total conditions of 546 R (303 K), 15.28 psi (105 352 N/m^2), and Mach number 0.697. The static equilibrium pressure of 11.03 psi (76 049 N/m^2) is set initially at the inflow plane, and a ambient static pressure of 14.3 psi set at the exit plane. The nozzle operates at a pressure ratio of 2.6 (37.15 psi / 14.3 psi).

B. Vortex Modeling

The tabs (mixing enhancement devices) were modeled as a pair of vortices on the inflow plane. The velocity vector field (*v*,*w* components) are modeled by a modified version of the Jacquin multiple-scale vortex model[11]:

$$v_{\theta}(r) = \frac{\Gamma_o \cdot (0.25 \cdot r_c \cdot r)^{0.5}}{2\pi} \quad for \quad r < r_c/4$$

$$v_{\theta}(r) = \frac{10 \cdot \Gamma_o \cdot r}{(2\pi \cdot r_c^2)} \quad for \quad r_c/4 \le r < r_c$$

$$v_{\theta}(r) = \frac{\Gamma_o}{(2\pi \cdot r^2)} \quad for \quad r \ge r_c$$

and Γ_o is the outer circulation, r is the radius from the point of interest to the center of the vortex, r_c is the radius of the vortex core, and θ is the angle from the center of the vortex to the center of the cell. A mapping from (r, θ) to (y, z) coordinates is used to obtain the v and w components of velocity from the tangential velocity.[12]

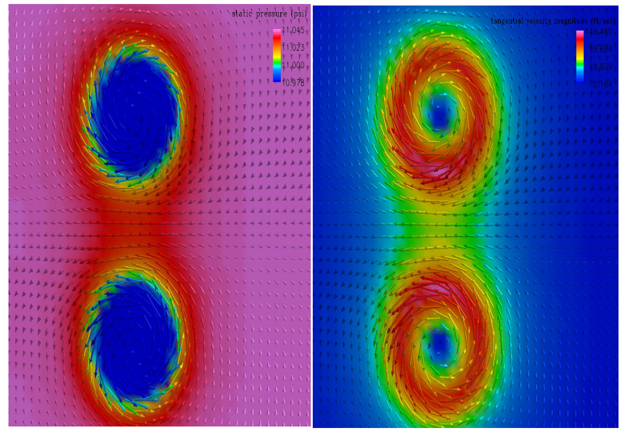

Figure 3: Initial static pressure field (left) and tangential velocity field (right) show details of a vortex pair that represents a tab. Note counter-rotating vortex cores and constant pressure in the cores.

It was necessary to modify the standard Jacquin vortex model so that a quadratic decrease in velocity profile existed outside the core to localize the effect of the vortices on the velocity vector field. This is a compromise between full solid body rotation and the shallow decay of velocity outside the core, characteristic of a Jacquin vortex model. These vortices can be placed anywhere on the inflow plane with different magnitudes, directions, and profiles independent of each other. In addition to the velocity field, a pressure model was developed such that the static pressure at any point in the core is assigned the pressure at the vortex core edge, which happens to be the lowest pressure value at any point within the field of the vortex (Figure 3). Consequently, stagnation pressure and temperature as well as Mach number vary across the vortex, providing for realistic vortices. No effort in this report has been put into measuring total pressure losses and blockage due to these relatively weak vortices, and the resulting effect on mixing and flow entrainment. But keeping tabs and blockage effects to minimums by using relatively weak vortices should lend itself well to determining if the tab orientations are even practical and effective in this nozzle.

The connection between physical tabs and vortex properties was provided through much experimental work with tabs completed by Foss & Zaman[6]. The vortex core radius was fixed to 0.1 inches and the nondimensional circulation was fixed to 0.24 for all tab sizes and cases. The relationship between tab size and the vortex properties is given by the following equation:

$$V_{\theta_{max}} = \frac{\Gamma_{nondim} \cdot \Delta U \cdot b}{2\pi r_c}$$

where $V_{\theta\ max}$ is the maximum tangential velocity, and r_c is the radius of the vortex core. Γ_{nondim} is the circulation, non-dimensionalized by ΔU, the shear velocity (1456 ft/sec), and *b*, the tab base length. Accordingly, 111 ft/sec was found for the maximum tangential velocity magnitude with the tab base length of 0.2 inches. Similarly, 222 ft/sec corresponds to a tab base length of 0.4 inches. Thus, the tab size is modeled solely by increasing or decreasing the velocity magnitude. Two vortices representing one tab were positioned laterally with the vortex core edges tangential to the hot lobe boundary with the vortex centers two diameters (0.4 inches) apart. The rotation direction of the vortices corresponds to the fact that the tabs deflect into the high speed flow at a 45 degree angle (cold flow is pulled into hot flow).

C. Grid Generation

The structured, computational grid was developed with Pointwise, Inc's GRIDGEN[9] software and contains 1 018 980 points with 108 points streamwise, 185 vertically, and 51 horizontally, distributed uniformly. Five grid points (for the fine grid) were set across the vortex core radius. The grid (Figure 4) is composed of 10 zones which aids application of different boundary conditions. The larger 10^{th} zone encompasses 95% of the computational domain (by volume). This was found to eliminate errors introduced due to zero-order extrapolation of the turbulence variables across zonal boundaries[8] in WIND v3.0.

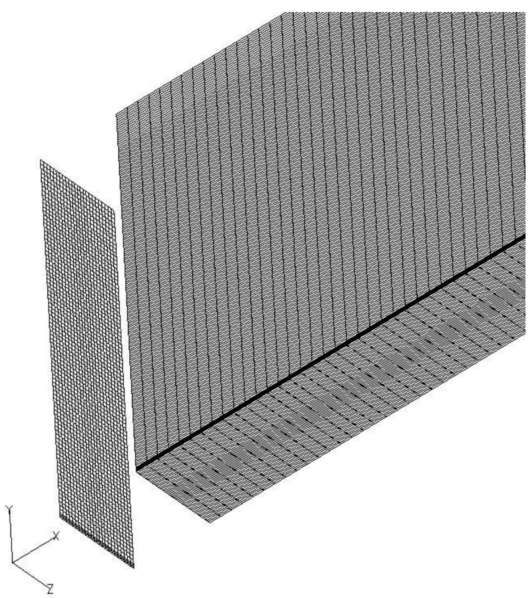

Figure 4: Details of grid zoomed on the nozzle entrance. Broken in pieces for clarity. Flow is from the negative *x* direction.

D. Flow Solution

The WIND v3.0 code[14] used for this analysis is a general purpose Reynolds-Averaged Navier-Stokes code. WIND is a product of the NPARC Alliance, a partnership between the NASA Glenn Research Center (GRC) and the USAF Arnold Engineering Development Center (AEDC), dedicated to the establishment of a national, applications-oriented flow simulation capability.[16]

The solver was configured to run at steady-state with the following specifications:

- node-centered finite-volume approach
- second order Roe upwind scheme
- TVD "compression" parameter of 1
- Two-equation k-ε turbulence model

A Fortran code was developed to preprocess the solution file once (prior to running the WIND code) and prescribe the inflow conditions and vortices at the inflow plane. This preprocessor serves three purposes: to assign hot and cold flow properties to points on the inflow plane, to insert vortices, and to generate smooth gradient regions in the cold sections that are bounding the hot.

The boundary condition for the cold, subsonic flow is *arbitrary inflow*, where the flow angles, stagnation temperature, and stagnation pressure are held at their intial values. The boundary condition for the hot section is *frozen*, fixing stagnation temperature, stagnation pressure, Mach number, flow angles, and turbulence variables. The outflow boundary condition is *downstream pressure*, specified at 14.3 psi. Supersonic points at the outflow plane are extrapolated. The walls are inviscid. The two-equation k-ε turbulence model[3] was employed for all cases using an intial value of turbulent kinetic energy of 15000 ft^2/sec^2 (4% turbulent intensity), and turbulent viscosity of 3.8e-5 slug/ft-sec. Previous work at Glenn on lobed nozzles has shown that this viscosity value is satisfactory. Compressibility and variable C_μ corrections were not used. The criterion for convergence was a reduction of at least two orders of magnitude for the L2 norm, and integrated mass and integrated stagnation enthalpy at any station downstream to be less than 1% deviation from the inflow (see Figure 5).

The Total Variation Diminishing (TVD) "compression" factor in WIND was set to a value of 1, instead of

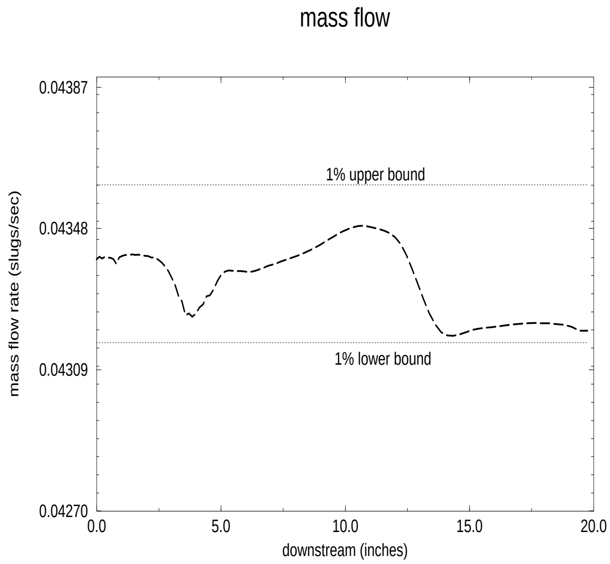

Figure 5: Mass flow plot for case without vortices showing the conservation of mass as indicated by the 1% bounding lines.

the default 2 for the second-order scheme being used. The TVD limiter limits the excessive fluctuations of properties around regions of high gradients and shocks[8,15].

WIND was configured to run in multi-processor mode (10 processors) using the SGI Origin2000 R10000 processor. CPU time for a turbulent solution was 972 microseconds per node-iteration.

E. Post Processing

To provide more concrete interpretations of qualitative pictures, many mixing parameters have been used to quantify the amount of mixing, but no universal parameter has been agreed upon. Three mixing parameters[1,4,5] have been investigated, two of them velocity based, and one based on temperature. The velocity based parameters are not monotonic due to shocks and expansions in the flowfield. The mixing parameter ω[5] is based on a mass-averaged stagnation temperature, an integral quantity. Its formula is given by:

$$\omega = \frac{\int \left| \rho u (T_o - T_{o_{ave}}) \right| dA}{\left[\int \left| \rho u (T_o - T_{o_{ave}}) \right| dA \right]_{ref}}$$

$$where \qquad T_{o_{ave}} = \int \rho u T_o dA$$

where T_o is the local total temperature, ρ is the local density, u is the streamwise velocity component, and dA is the incremental area across which the integral is evaluated. The denominator is the reference plane chosen to be the inflow plane of the nozzle for the case without vortices.

3. Results

A. Description of Cases

Seven cases were completed as part of the parametric study of the mixer/ejector nozzle with and without vortex structures. The number, location, and the tangential velocity magnitude of the vortices were varied. Insight into the effects of different diffusion processes (turbulent diffusion and streamwise vorticity), relevant to the parametric study, can be ascertained from these solutions. Mixing for this problem is dominated by turbulent diffusion and additional mixing is provided through large-scale streamwise vorticity. There is no transverse mixing due to the lobes themselves (flow is entirely axial coming into the mixer). The seven cases comprising the parametric study consist of one case involving no tabs, and six cases involving three different tab positions on the lobe at two different vortex strengths (vortex maximum tangential velocity magnitude). The two different vortex strengths correspond to a tab base lengths of 0.2 inches (small tab) and 0.4 inches (large tab) with tangential velocities of 111 ft/sec and 222 ft/sec respectively. The three different placement schemes are shown in Figure 6.

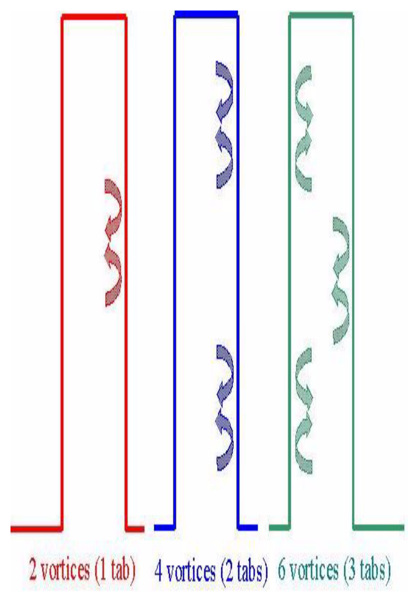

Figure 6: The three schemes for tab placement for the parametric study.

B. Grid Dependence

Two grid sizes were tested for this problem. Due to computing limitations, it was only practical to run these two cases. All of the results presented here were completed with the fine grid. Shown in Figure 7 is integrated static temperature for the case without vortices for the two different grid sizes tested. These results indicate that the coarse grid is close to the results of the fine grid, and this grid size, 51x185x108, was chosen for the final calculations.

C. Evaluation of Model

A baseline solution with no vortices was computed

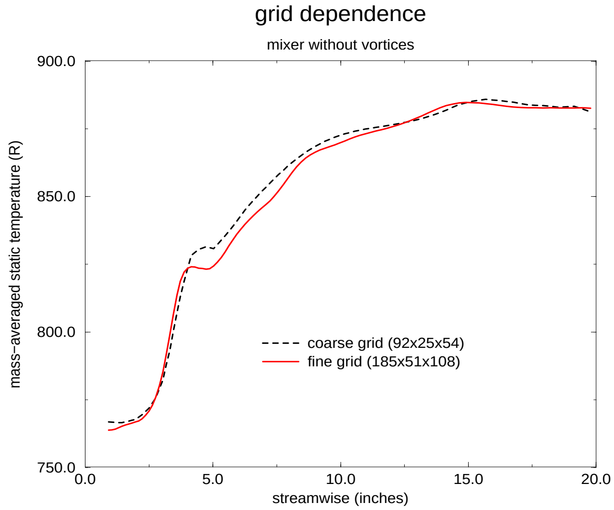

Figure 7: Mass-averaged static temperature plot for coarse and fine grids without vortices

as a reference case to compare with the solutions containing vortices, and to provide an indication of the additional “amount” of mixing that the vortices themselves have induced. The case without vortices was qualitatively compared to analogous CFD and laboratory results obtained as part of the HSR program at Glenn. The contours of stagnation temperature and

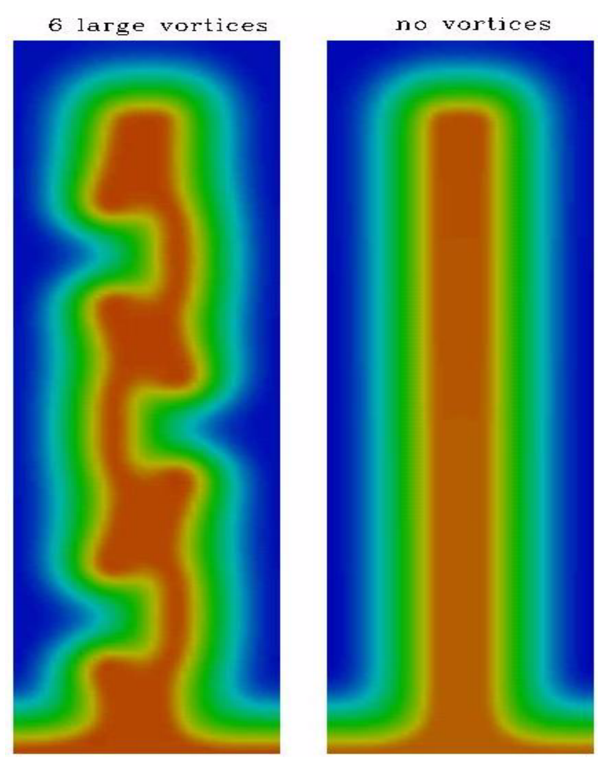

Figure 8: Static temperature contours with no vortices, right, and 3 tabs, left. Note large-scale distortion of lobe structure 2.8 inches downstream.

streamwise velocity component in previous studies were seen to have similar patterns at the duct exit, but some differences arise due to the multiple-lobe geometry used in these studies. Better insight into the vortex characteristics and impact of vortices on the flowfield can be gathered from Figures 8 and 9 showing static temperature contours with vortices (left) and without vortices (right), with cuts at the nozzle entrance, 2.8 and 5 inches downstream. In Figure 9 the primary vorticity is highlighted by the function *helicity*, defined as the dot product of the velocity and vorticity vectors. The color grey indicates clockwise rotation and purple indicates counter-clockwise rotation. These figures demonstrate that vorticity is being convected downstream which leads to large scale distortion of the original lobe shape. Also apparent is the strong viscous diffusion due to the viscosity of the k-ε model.

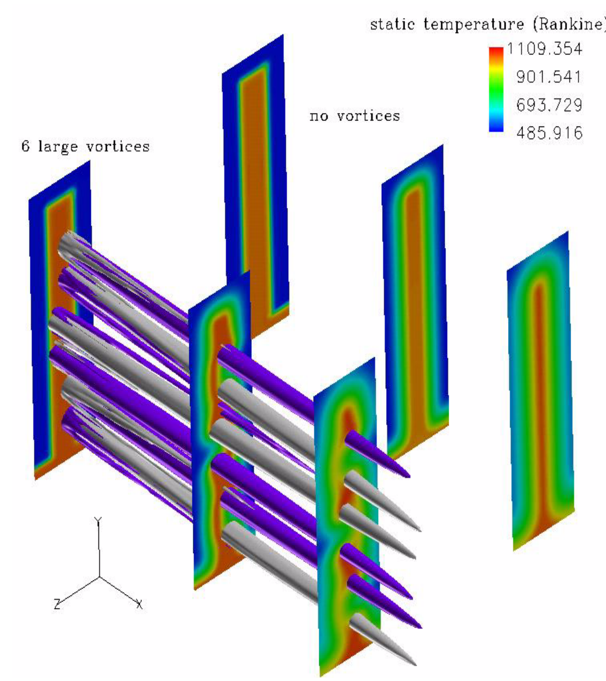

Figure 9: Comparison of the effects of tabs colored by static temperature and helicity for the first 5 inches of the nozzle. Lobe without vortices (right) and lobe with 3 tabs (left) highlighting flow structure distortion. The flow direction is from the back to the front.

D. Effect of Tabs on Mixing

Figures 10-17 show cuts of static temperature, Mach number, stagnation temperature, u-velocity, turbulent viscosity, turbulent dissipation, turbulent kinetic energy, and vorticity magnitude respectively, across the duct for no vortices (left) and six vortices representing large tabs (right). Flow is from left to right. It is readily

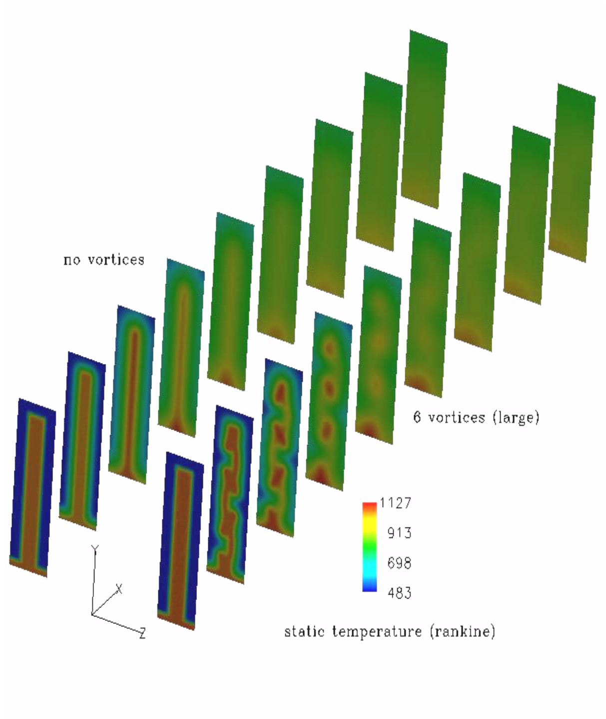

Figure 10: Static temperature contours with and without vortices.

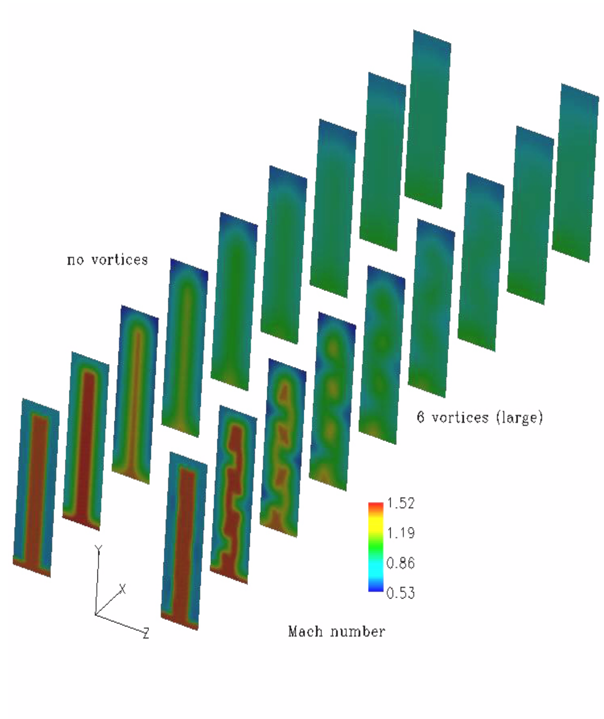

Figure 11: Mach number contours with and without vortices

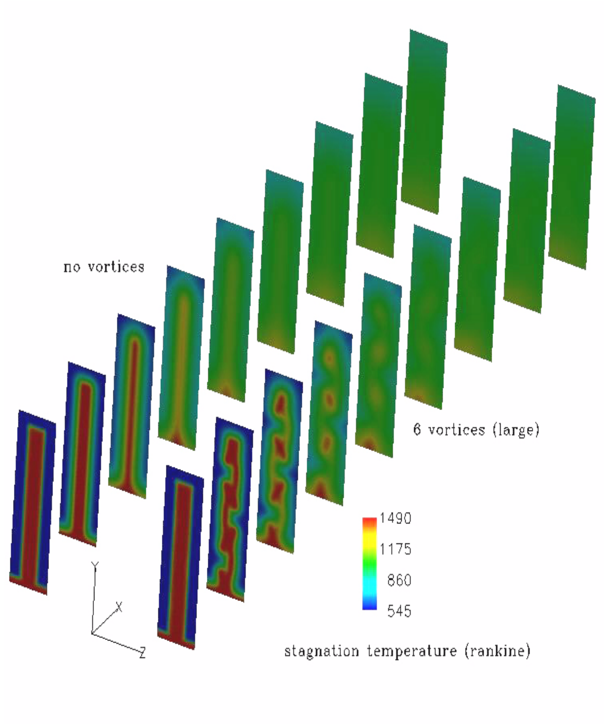

Figure 12: Stagnation temperature contours with and without vortices

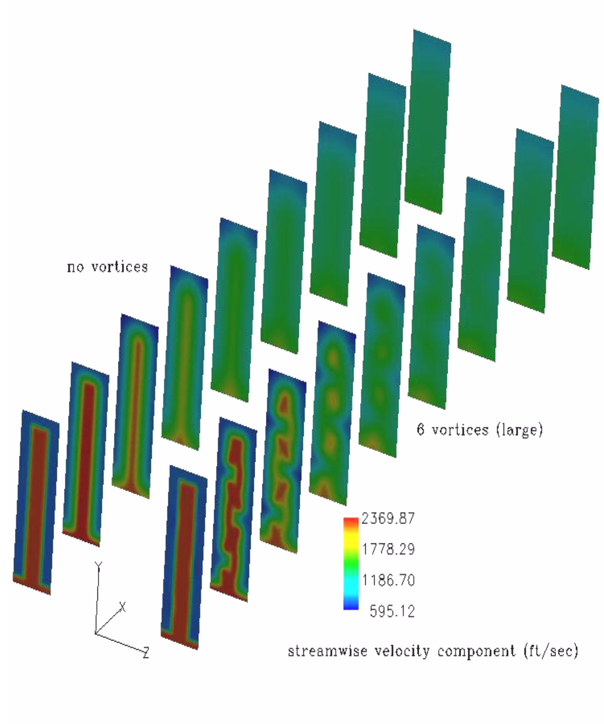

Figure 13: U-velocity contours with and without vortices

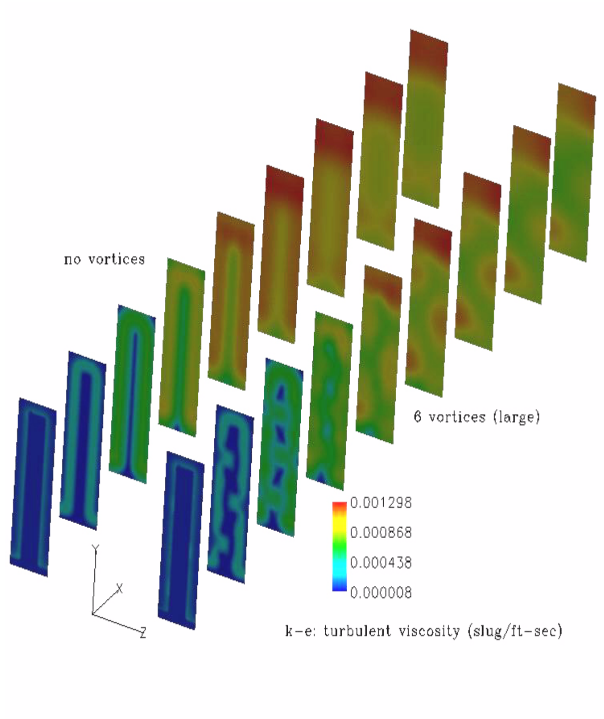

Figure 14: Turbulent viscosity contours with and without vortices

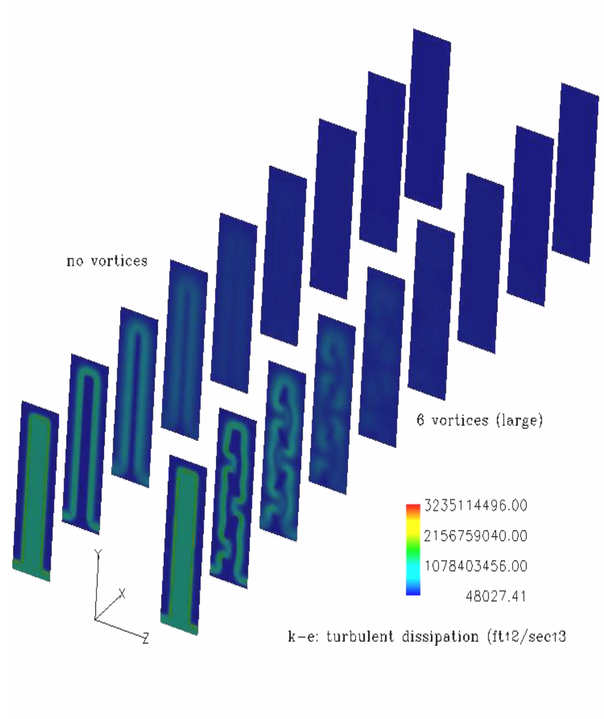

Figure 15: Turbulent dissipation contours with and without vortices

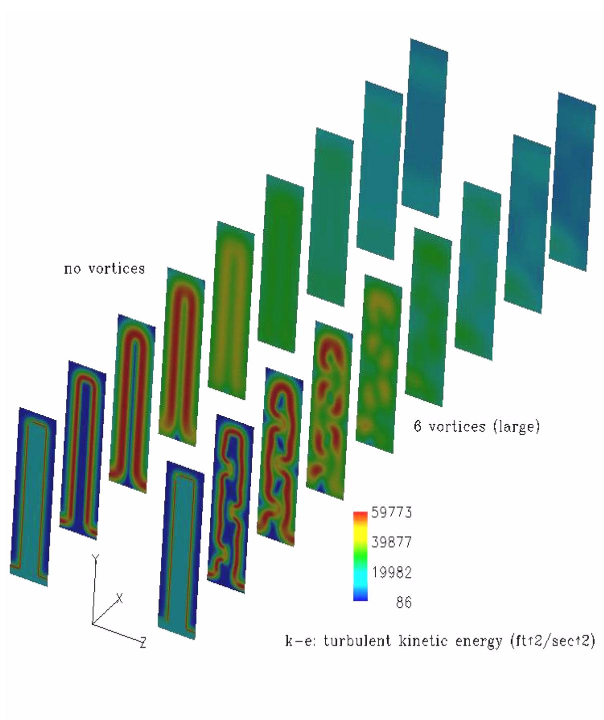

Figure 16: Turbulent kinetic energy contours with and without vortices

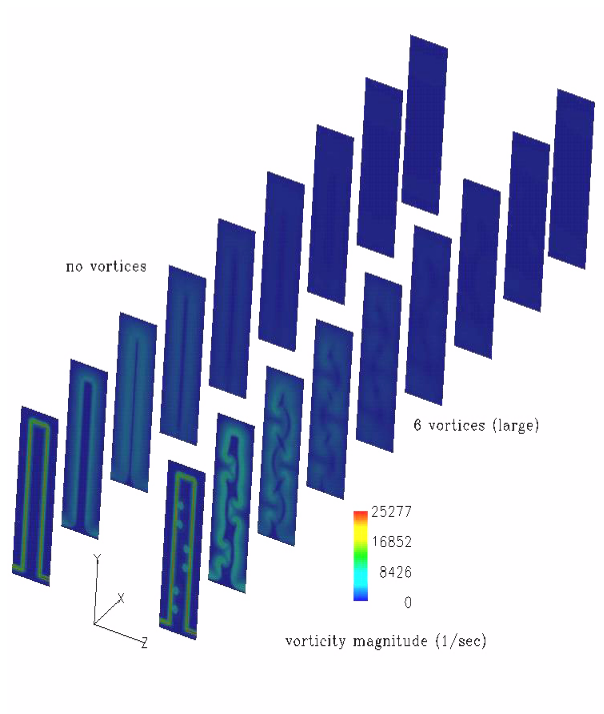

Figure 17: Vorticity magnitude contours with and without vortices

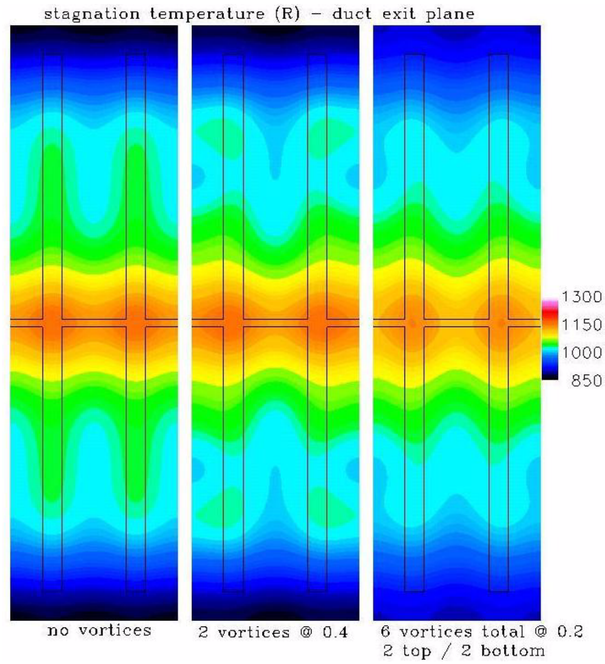

Figure 18: Contour plots of stagnation temperature at exit plane highlighting differences due to tab sizing and placement. Mirrored in the horizontal and vertical directions; black lines represent lobe boundaries.

apparent from these figures that the vortices have significantly altered the structure of the flow and the lobed-shaped structure itself. Mixing differences at the exit plane are not obvious. However, looking at Figure 18 of stagnation temperature at the exit plane, one can see in the left image that a faint lobe is apparent and that the flow has not mixed completely out. Definite differences can be seen between the left and middle images, indicating that the vortices arguably have an impact at the exit of the duct.

Quantitatively, the additional mixing, just downstream of the mixer, can be seen from the mixing parameter ω in Figures 19 and 20. Figure 19 shows that the additional mixing is small for all cases, but Figure 20 shows definite proof that vortices are contributing to mixing throughout the middle portions of the duct. Curves lower in Figures 19 and 20 represent values of increased mixing (ω=1 is fully unmixed and ω=0 is fully mixed). The mixing values in all three cases start out the same and then diverge as expected indicating different mixing rates. Six vortices representing large tabs produce the most mixing of any case that was part of the parametric study.

In addition to the faint and smeared lobe structure at the exit plane, regions of unmixed flow are seen to exist at the top, center, and bottom of the duct (Figure 18). This is consistent with findings in previous work. Previous techniques have focused on placing tabs on the vertical walls of the lobes as was done in this parametric study (Figure 6), and have shown little affect on the unmixed regions. An additional study was performed above and beyond the original scope of the parametric study in attempt to affect these unmixed regions. Additional vortices (small size) were placed at the top and bottom of

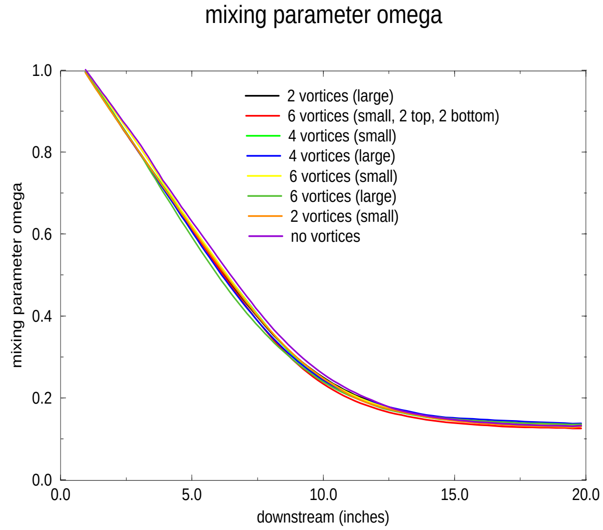

Figure 19: Plot showing mixing parameter ω for all cases.

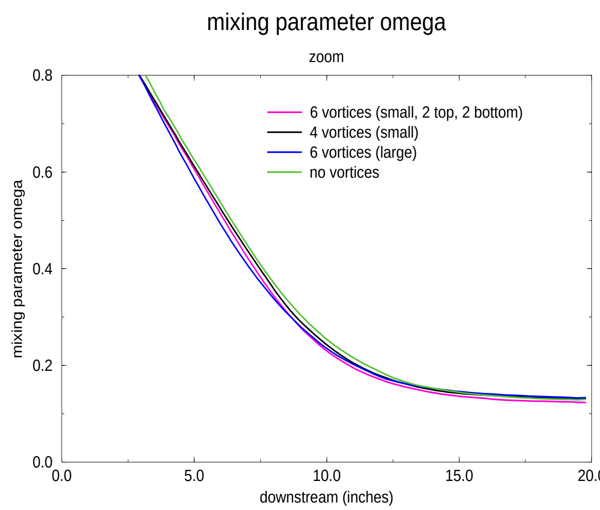

Figure 20: Zoom highlighting mixing differences (using ω) for some cases.

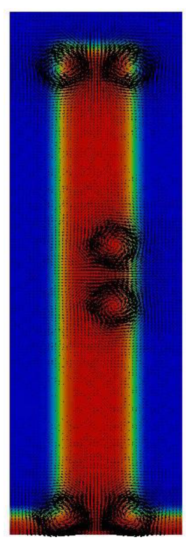

Figure 21: Vortex locations to investigate mixing in the vertical direction (vectors shown in black for clarity).

the lobes as seen in Figure 21. It is shown that tabs at the top and bottom improve the mixed state even more (Figure 18, right image). The unmixed regions of cold flow at the top and the region of hot flow at the bottom have been diffused, resulting in a more mixed state. This is also shown quantitatively in Figure 20, where mixing has been improved at the exit. These changes in mixing are small, but do indicate that putting tabs at the top and bottom holds promise for more mixing and lowering the exit jet noise. This technique of quick placement of vortices provides an efficient way to evaluate and optimize placement of tabs. These schemes, and other more elaborate tab arrangements, could be addressed more formally in a subsequent study.

4. Conclusions

A parametric study of mixer/ejector nozzle modeling one lobe and associated tabs has been conducted to evaluate the effect of the tabs on mixing. These tabs have been modeled by pairs of vortices, and the placement, size, and number of vortices have been studied. It has been shown that mixing due to the tabs is most apparent in the middle portion of the duct, and the tabs have significantly altered the lobe and flow structure. They have a small, but noticable effect at the duct exit. The data has shown that the vorticity associated with the large tabs can mix out the lobed structures, and promote good lateral mixing. No effort in this report has been put into measuring total pressure losses and blockage due to the vortices, and the resulting effect on mixing and flow entrainment. But keeping tabs and blockage effects to minimums by using relatively weak vortices should lend itself well to determining if the tab orientations are even practical and effective in this nozzle. The overall conclusion is that placement of tabs at the top and bottom of the lobe induce vertical mixing and diffuse unmixed regions seen in the parametric study. The preprocessor allows quick placement of vortices in the flowfield, and has proven to be a good tool for optimizing the placement of tabs in lobed mixers.

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13. ABSTRACT ***(Maximum 200 words)***
A numerical study employing a simplified model of the High Speed Civil Transport mixer/ejector nozzle has been conducted to investigate the effect of tabs (vortex generators) on the mixing process. More complete mixing of the primary and secondary flows within the confined ejector lowers peak exit velocity resulting in reduced jet noise. Tabs were modeled as vortex pairs and inserted into the computational model. The location, size, and number of tabs were varied and its effect on the mixing process is presented here both quantitatively and qualitatively. A baseline case (no tabs) along with six other cases involving two different vortex strengths at three different orientations have been computed and analyzed. The case with the highest vorticity (six vortices representing large tabs) gives the best mixing. It is shown that the influence of the vorticity acts primarily in the forward or middle portions of the duct, significantly alters the flow structure, and promotes some mixing in the lateral direction. Unmixed pockets were found at the top and bottom of the lobe, and more clever placement of tabs improved mixing in the vertical direction. The technique of replacing tabs with vortices shows promise as an efficient tool for quickly optimizing tab placement in lobed mixers.

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