AIAA 80-0008R

Numerical Modeling of a 7-Tube Nozzle/12-Lobe Mixer Jet Flow

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Abstract

CALCULATED and measured flow properties are presented for the downstream development of a heated subsonic jet exhausting into a still ambient. The jet issues from a 7-tube nozzle having a 12-lobe internal mixer upstream of the nozzle exit. The numerical method employed solves the parabolized compressible Navier-Stokes equations in concert with a two-equation turbulence model. Calculated mean flow properties and axial turbulence intensity are in good agreement with test data. The results demonstrate the applicability of the three-dimensional analysis in evaluating the effects of changes in the initial mean flow profiles on the downstream development of jets from mixer/nozzle systems.

Contents

Multitube nozzles and mixer/nozzle combinations have been considered for several years in jet noise reduction studies. The design and evaluation of these nozzles is based primarily on a combination of model and full-scale parametric testing. In general, it is not practical to evaluate all possible alternatives experimentally, so new designs rely heavily on the available data base. The desire to study nozzle configurations for which no such data base exists is a major incentive for the current interest in developing reliable numerical design procedures. The present results for the 7-tube nozzle/12-lobe mixer provide a step toward using numerical flow analysis methods in the design process.

The analysis employs the mass-averaged form of the parabolized three-dimensional Navier-Stokes equations with a two-equation (k-ϵ) turbulence model. Streamwise diffusion is neglected and the axial pressure gradient is zero. The fluid is assumed to be an ideal gas and the ratio of specific heats is a function of the local total temperature. The details of the equations and the turbulence model can be found in Refs. 1-3 along with a discussion of the implications of the parabolic approximation.

The data consist of total temperature, total pressure, and axial turbulence intensity measurements. Velocity and static temperature were calculated assuming that the static pressure in the jet was uniform and equal to the ambient pressure. A discussion of the mean flow and turbulence data and the experimental facilities is contained in Ref. 3. The values of velocity and static temperature at the nozzle exit obtained from the measurements were used as initial conditions for the analysis. In addition, the initial turbulence energy k (normalized by the peak velocity squared) was set to 0.01 in the mixing regions and half that value outside the mixing regions. The initial turbulence dissipation ϵ was calculated from $\epsilon = (0.09)^{3/4} k^{3/2}/\ell$ where the length scale ℓ was estimated as about 10% of the initial shear layer width in the mixing regions and twice that elsewhere.

The comparisons of predictions and measurements are presented in Figs. 1 and 2 for the total velocity and in Fig. 3 for the axial turbulence intensity. Values of the axial turbulence intensity were calculated from the predicted values of turbulence energy by assuming a relationship between the fluctuating velocity components. Available mixing layer data indicate that the axial turbulence intensity is about 23% larger than the transverse intensities, which are taken as equal. Figure 4 illustrates, with respect to the tube nozzle, the locations of the profiles of Figs. 1-3. The velocities and turbulence intensities are normalized by the nozzle exit peak velocity V_{REF}. The radius and axial distances are normalized by the diameter of a round nozzle having the equivalent area of the 7-tube nozzle D_{REF}.

The 7-tube nozzle/12-lobe mixer combination produces inverted velocity and temperature profiles at the nozzle exit,

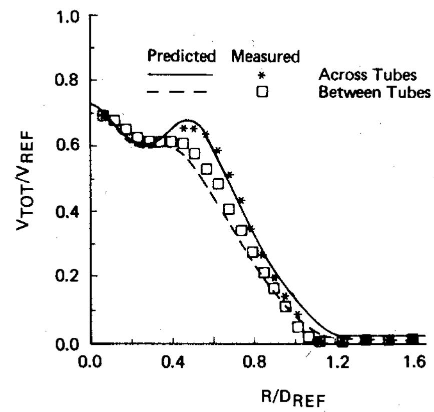

Fig. 1 Velocity profiles at 2.5 diameters downstream.

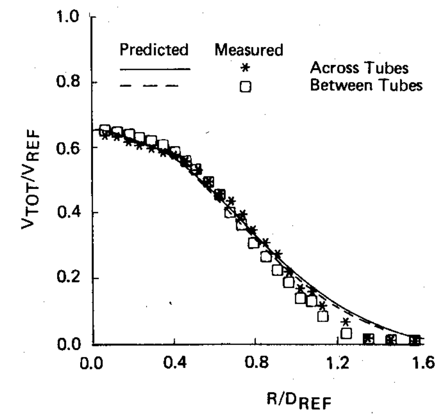

Fig. 2 Velocity profiles at 5.0 diameters downstream.

Presented as Paper 80-0008 at the AIAA 18th Aerospace Sciences Meeting, Pasadena, Calif., Jan. 14-16; submitted March 7, 1980; synoptic received Sept. 5, 1980. Full paper available from AIAA Library, 555 W. 57th Street, New York, N.Y. 10019. Price: Microfich, $3.00; hard copy, $7.00.

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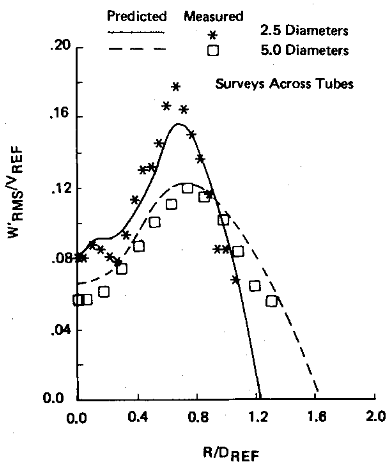

Fig. 3 Turbulence intensity profiles at 2.5 and 5.0 diameters downstream.

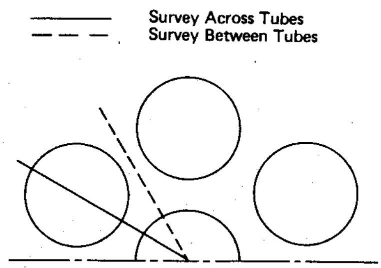

Fig. 4 Location of flow surveys.

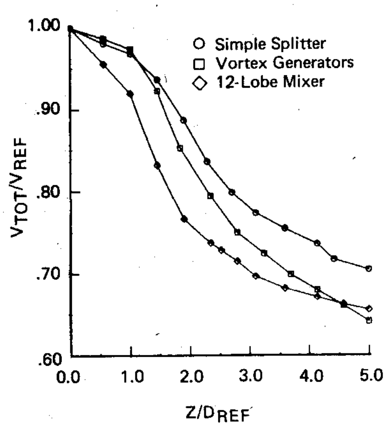

Fig. 5 Peak velocity decay for three internal mixers.

i.e., the high-velocity and high-temperature fluid surrounds lower velocity, cooler fluid. At 2.5 diameters downstream, the peak velocity is on the centerline (see Fig. 1) and the surveys between the tubes and across the tubes produce two distinctive profiles. At 5 diameters downstream (Fig. 2) the two profiles are nearly identical, indicating that the flow is approaching axisymmetry. This is well represented by the predictions.

The predicted axial turbulence intensities at 2.5 diameters downstream (Fig. 3) correctly reproduce the trends in the measurements; however, the maxima are slightly underpredicted. At 5 diameters downstream the predicted and measured turbulence intensities are in pretty good agreement (see Fig. 3). (Reference 3 discusses some problems encountered in measuring the turbulence intensities for the 7-tube nozzle.)

Reference 3 presents computed and measured results for two additional internal mixers, a simple splitter and vortex generators. The purpose of a mixer is to enhance mixing. As seen from Fig. 5 the 12-lobe mixer reduces the peak velocity faster than either the simple splitter or the vortex generators. Although the three different mixers produce highly disparate nozzle exit profile shapes, the present analysis correctly predicts the jet behavior based on the available experimental data. (See Ref. 3 for further details.)

In solving the given system of equations for jet flows, large gradients in flow properties at the nozzle exit place stringent restrictions on the magnitude of the allowable axial step size. To alleviate this restriction the solution is iterated several times between adjacent planes as the solution is marched downstream. The iteration between planes is necessitated primarily because of the nonlinearities in the turbulence model. In addition, an iteration is performed in the tridiagonal solver when solving the pressure equation (see Ref. 3). This iteration ensures mass conservation by providing the cross-plane pressure field corresponding to a mass-conservative cross-plane velocity field.

The initial conditions for turbulence kinetic energy k and turbulence length scale ℓ were estimated based on available mixing layer data and experience. (The dissipation is computed from the energy and length scale as mentioned above.) A brief parametric study was conducted to ascertain the impact of initial values of k and ℓ on the mean flow quantities downstream. Four cases were run with k being varied by a factor of four and ℓ by a factor of two. The changes in k and ℓ did have some effect on the mixing rate, particularly in the region just downstream of the nozzle exit; however, the overall solution did not appear to be sensitive to small changes in these initial values.

In addition to errors incurred in specifying the initial conditions, errors can result from using too coarse a mesh. The impact of the mesh density was considered by independently halving the mesh in the radial and circumferential directions from the original nonuniform 44×14 mesh. Noticeable changes occurred in the solution for the reduced circumferential mesh (44×7) but negligible change occurred for the halved radial distribution (22×14). The original mesh was accepted as sufficient for the problem.

The numerical method successfully computed the jet development from a 7-tube nozzle with strong variations in nozzle exit velocity profile shape. It is concluded that the parabolized Navier-Stokes equations can be reliably used to predict changes in mean flow properties downstream of multitube nozzles with strong variations in initial profile shapes. While the qualitative trends in turbulence data were correctly predicted, the quantitative accuracy to which these properties can be predicted remains to be established, due to the uncertain quality of the available turbulence data for this type of flow. The numerical method could be used to replace parametric model scale testing in the design of multitube nozzles where knowledge of the mean flow properties as a function of nozzle geometry and initial conditions is of primary importance.

References

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[3]Barton, J.M. and Birch, S.F., "Numerical Modeling of Three-Dimensional Turbulent Jet Flows," Paper 80-0008 presented at AIAA 18th Aerospace Sciences Meeting, Pasadena, Calif., Jan. 1980.