ANALYTICAL STUDY OF FLOW PHENOMENA IN SSME TURNAROUND DUCT GEOMETRIES

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ABSTRACT

The SSME fuel turbopump hot gas manifold has been identified as a source of loss and flow distortion which significantly affects the performance and durability of both the drive turbine and the LOX injector area of the main combustion chamber. The turnaround duct is the axisymmetric part of the manifold at the exit of the turbine. The geometry is characterized by high wall curvature in the 180 degree turnaround region and the flow is essentially incompressible with a 9.37 degree swirl component out of the turbine. The fundamental flow phenomena in this duct have been investigated using the ADD code, an axisymmetric, viscous, marching code developed under contract by UTRC for LeRC.

Two current SSME geometries were studied, the Full Power Level (FPL) and the First Manned Orbital Flight (FMOF) configuration. Additional studies were conducted for the effects of turnaround duct geometry on flow losses and distortions, by varying wall curvature and flow area variation in the 180° turnaround region. The effects of the duct inlet flow phenomena such as the radial distortion of the inlet flow and inlet swirl level on turnaround duct performance were also investigated. Results show that of the two current geometries, the FMOF configuration had lower pressure losses and generated less flow distortion, but had a small flow separation bubble at the 180° turnaround exit. The study of the geometry effects has shown that by optimizing wall curvature and flow diffusion in the turnaround, improved duct performance can be achieved.

INTRODUCTION

The SSME fuel turbopump hot gas manifold has been identified as a source of loss and flow distortion which significantly affects the performance and durability of both the drive turbine and the LOX injector area of the main combustion chamber. The turnaround duct is the axisymmetric part of the manifold at the exit of the turbine. The geometry is characterized by high wall curvature in the 180 degree turnaround region and the flow is essentially incompressible with a 9.37 degree swirl component out of the turbine. The fundamental flow phenomena in this duct are being investigated using the ADD code, an axisymmetric, viscous, marching code developed under contract by UTRC for LeRC.

Two current SSME geometries were studied, the Full Power Level (FPL) and the First Manned Orbital Flight (FMOF) configuration. Additional studies were conducted for the effects of turnaround duct geometry on flow losses and distortions, by varying wall curvature and flow area variation in the 180^{o} turnaround region. The effects of the duct inlet flow phenomena such as the radial distortion of the inlet flow and inlet swirl level on turnaround duct performance were also investigated.

ADD CODE DESCRIPTION

The viscous duct code used, A.D.D. code, handles turbulent swirling compressible flow in axisymmetric duct configurations. Flow separation can be predicted, but results cannot be computed past a point of separation if this separation is a significant part of the flow passage. At the high Reynold's numbers in air, consistent with SSME flow conditions, the solution is neutrally stable in the high curvature region of the TAD. The instability and numerical errors were localized to the inner wall of the turnaround where wall curvature is high and the boundary layer is grossly modified by the pressure gradients in the duct. The duct geometries were modeled from fuel turbine exit to the entrance of the middle transfer duct (i.e., the axisymmetric region of the exit duct). Two inlet flow profiles were used. The first is a uniform inlet with thin wall boundary layers, and the second is a radially distorted flow based on three-dimensional Euler code calculations through the fuel turbine.

TURNAROUND DUCT GEOMETRIES

The A.D.D. code mesh setup was developed to provide acceptable stability and computation times while capturing the physics of the flow. The meshes shown were standardized to be 100 streamline and 90 potential lines for $9x10^4$ total grid points. The mesh distortion of model the wall boundary layers was chosen to yield the first mesh point off the wall at a Y^+ of 1.0. Typical A.D.D. code runs on the CRAY-1S were 3 to 3.5 cpu minutes.

TAD DESIGN INLET CONDITIONS

This study was done with air as the working fluid. The design inlet temperature and swirl were used and the flow and inlet pressure were adjusted to match design inlet Reynold's number and mach number.

RESULTS FOR UNIFORM INLET

The results for the uniform inlet indicate that the majority of the duct loss is generated on the inner wall of the turnaround which has high surface curvature and higher mach numbers. Problems with numerical instability are also greatest in this region. The rapid flow acceleration on the inner wall causes the boundary layer to be reduced and shear stresses to become large.

The FPL TAD results are shown for the mach number profiles through the duct at each potential line. The figure shows the velocity peaking near the inner wall of the turnaround section and a resulting velocity deficit near that wall is shown at the duct exit indicating the high loss region. No flow separation or potential separation was indicated by the results for the FPL duct.

The FMOF TAD mach number profiles are also shown for uniform inlet flow. The FMOF geometry differs from the FPL in that the inner wall of the turn has a smaller radius resulting in higher inner wall curvature and a slight area increase from turnaround inlet to turnaround exit. Velocity peaks similar to those in the FPL are seen near the inner wall of the turnaround section and the velocity deficit region at TAD exit is also similar to the FPL duct. However, at the turnaround section exit on the inner wall the shear stress goes to zero indicating possible flow separation, although the calculated separation was only a small region of the flow for about 10 potential lines.

The calculated total pressure losses, based on the difference in mass averaged values of total pressure ratio to the inlet dynamic pressure, were significantly different for the two ducts. The losses were 0.096 and 0.069 for FPL and FMOF configurations, respectively. The larger FPL loss can be attributed to the higher wall shear stresses on both walls from 90 to 180° in the turnaround region. These high stresses are probably due to higher velocities in this region as there is an area contraction of 23 percent through the 180° turnaround for the FPL configuration.

TAD WALL SHEAR STRESSES

The variations in wall shear stresses are shown in the figure on hub and tip walls for FPL and FMOF ducts for the uniform inlet flow case. The turnaround region begins and ends at the X/LREF value of 0.225 for both ducts. This region on the tip wall shows the high wall shear stresses and numerical instabilities on the high curvature inner wall of the turnaround for both duct geometries. Comparison between FPL and FMOF results in this region show that the higher curvature of the FMOF yields higher shear stresses on the tip wall for the first 90 degrees of the turnaround, but diffusion of the flow by the FMOF geometry results in significantly lower shear stresses from 90° to turnaround exit where stresses go to zero. The hub wall shear stresses are also lower for FMOF from 90° through turnaround to the exit due to lower velocity level.

RESULTS FOR DISTORTED INLET

The regions of high loss identified for the case of uniform inlet flow were not changed by the distorted inlet profiles for either the FPL or the FMOF duct. The comments above are still valid. The distorted inlet flow profiles are, however, somewhat mixed out passing through the TAD geometries.

The variation of Mach number profiles through the two TAD geometries is shown in the figure for the distorted inlet flow. The inlet distortions in mach number are mixed out and eliminated after entering the turnaround region for both ducts. Subsequent flow patterns downstream are similiar to those with uniform inlet conditions.

A comparison of total pressure losses between uniform inlet and distorted inlet indicates an increase in loss occurred for both TAD configurations. The losses were 0.105 and 0.086 for FPL and FMOF ducts, respectively. These increases in loss, based on percent of loss with uniform inlet were 9 and 25 percent for FPL and FMOF ducts, respectively. The FMOF geometry is apparently more sensitive to inlet flow distortion.

TOTAL TEMPERATURE VARIATION FOR DISTORTED INLET

A significant gradient in total temperature exists at fuel turbine exit, based on Denton code results. The radial distribution in total temperature at each potential line through the duct is shown. Only the FMOF results are shown since they are very similar to the FPL results. While the maximum difference in total temperature across the duct passage has been reduced from inlet to exit of the ducts, significant radial distortion still exists.

GEOMETRY STUDY RESULTS

The study of the two available SSME-TAD geometries has shown where the majority of losses are generated in the turnaround region. The results indicate a sensitivity to turnaround wall curvature and flow diffusion (streamwise area variation). Therefore, to check the sensitivity of loss to these parameters, a series of modified geometries were run on the ADD code using the uniform inlet flow profile. The basic premise was to minimize turnaround wall curvature within the radii envelope of the FPL and FMOF geometries and then to vary the area distribution through the turnaround so as to minimize the wall shear stresses in this region.

The overall results of this limited parametric study are shown. The parameter chosen to identify goodness was the TAD total pressure loss. The figure shows the variation of loss with the axial location of the center of the hub wall arc of the turnaround. For this series of cases the inlet area and exit area of the turnaround are equal, with the area being increased in the turnaround region by moving the hub arc center along the axis of rotation. Peak velocities are thereby lowered in the turnaround and wall shear stresses will be reduced in some areas. The trend shown in the figure indicates that loss is reduced as the center is moved out along the axis of rotation which increases the diffusion in the turnaround. No mimimum loss is calculated, instead flow separation on the hub wall is encountered. Calculations could not proceed past this point due to code limitation of no gross flow separation. However, similiar improvements can be obtained within a smaller envelope, i.e., reduced axial position of hub arc center, by introducing an overall area increase from turnaround inlet to exit. The tip wall radius in the turnaround was reduced incrementally but the inlet area was held constant, thereby increasing the area at turnaround exit. The figure shows the trend in loss with tip arc radius. A minimum loss value of 0.067 obtained at an hub arc center axial position of 1.45 inches and a tip arc radius of 0.60 inches.

The mach number profiles through the modified TAD are shown in the next figure. While the peak velocity region on the tip arc and deficit in velocity at the exit are still present the overall distortion was reduced. It should be noted that the inlet section upsteam of the turnaround accelerates the flow somewhat to allow a larger tip arc radius and therefore reduced wall curvature in the turnaround. The shear stresses are shown in the figure for hub and tip walls. Again the location of the tip arc center is about 0.225 while the hub arc center is about 0.261(X/LREF). The shear stresses in the turnaround are significantly reduced in comparison to the FPL geometry on both hub and tip walls. Comparison with the FMOF geometry is not quite as dramatic, but the flow separation bubble has been eliminated and peak shear stresses are less for the MOD TAD in the turnaround region.

TAD FLOW AREA DISTRIBUTIONS

The flow area distributions for three TAD geometries, (FPL, FMOF, and MOD) are shown in the figure. As can be seen, the area distributions in the 180° turnaround cover the range of possibility with area decrease (FPL), nearly constant area (FMOF) and area increase (MOD). Note that the inlet and exit flow areas are the same for the three ducts with an exit-to-inlet area ratio of 1.128 overall.

REFERENCES

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2. Anderson, O. L., Hankins, G. B., and Edwards, D. E., "Extensions to an Analysis of Turbulent Swirling Compressible Flow for Application to Axisymmetric Small Gas Turbine Ducts," NASA CR-165597, 1982.

3. Anderson, O. L., Hankins, G. B., and Edwards, D. E., "Users Manual for Axisymmetric Diffuser Duct (ADD) Code. Vol. 1 - General ADD Code Description, Vol. 2 - Detailed ADD Code Description, and Vol. 3 - ADD Code Coordinate Generator," NASA CR-165598, 1982.

4. McLallin, K. L., Kofskey, M. G., and Civinskas, K. C., "Effects of Interstage Diffuser Flow Distortion on the Performance of a 15.41-Centimeter Tip Diameter Axial Power Turbine," NASA TM-83359 and AIAA 83-1179, 1983.

TAD SWIRL STUDY

The sensitivity of the FPL and FMOF geometries to inlet swirl angle were studied. The inlet swirl angle was varied from 0 to 50° in 10° increments. The ADD code results are shown in the figure in terms of total pressure loss. Inlet values of total pressure, total temperature, and boundary layer displacement thickness, as well as axial mach number were held constant for this study (uniform inlet conditions). Therefore, the level of absolute inlet mach number increases with increasing swirl angle. This inlet mach number never exceeds 0.3.

The results indicate that losses decrease with increasing swirl levels until a minimum loss is reached. Continued increases in swirl angle then result in increasing losses. The mimimum loss swirl angles were approximately 45° and 30° for FPL and FMOF ducts, respectively. While the FMOF configuration has lower losses over the entire swirl range investigated, the FPL configuration exhibited more sensitivity to inlet swirl. The reductions in loss from zero swirl to minimum loss swirl were 12.3 and 3.8 percent for FPL and FMOF ducts, respectively.

ADD CODE DESCRIPTION

TECHNIQUE

- Compressible Viscous Space Marching Solution
- Laminar or Turbulent Flow
- Orthogonal Coordinate System with Mesh Packing in Boundary Layers

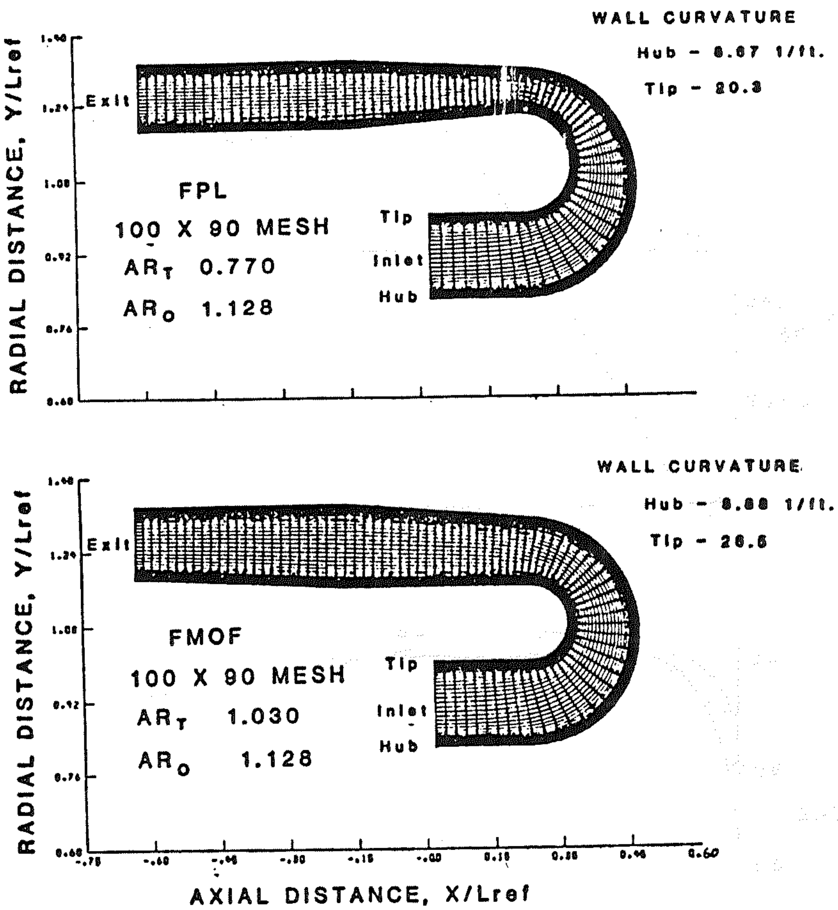
APPLICATIONS

- Axisymmetric Ducts
- Turbulent, Swirling, Compressible Flow
- Struts and Guide Vanes Using Correlated Airfoil Data
- Cooling Slots and Bleed on Walls

RESULTS

- Gas Turbine Interstage Diffuser - Axial Flow
- Radial Turbine Inlet Duct and Exhaust Diffuser
- SSME Turnaround Duct Fuel Turbine Exit

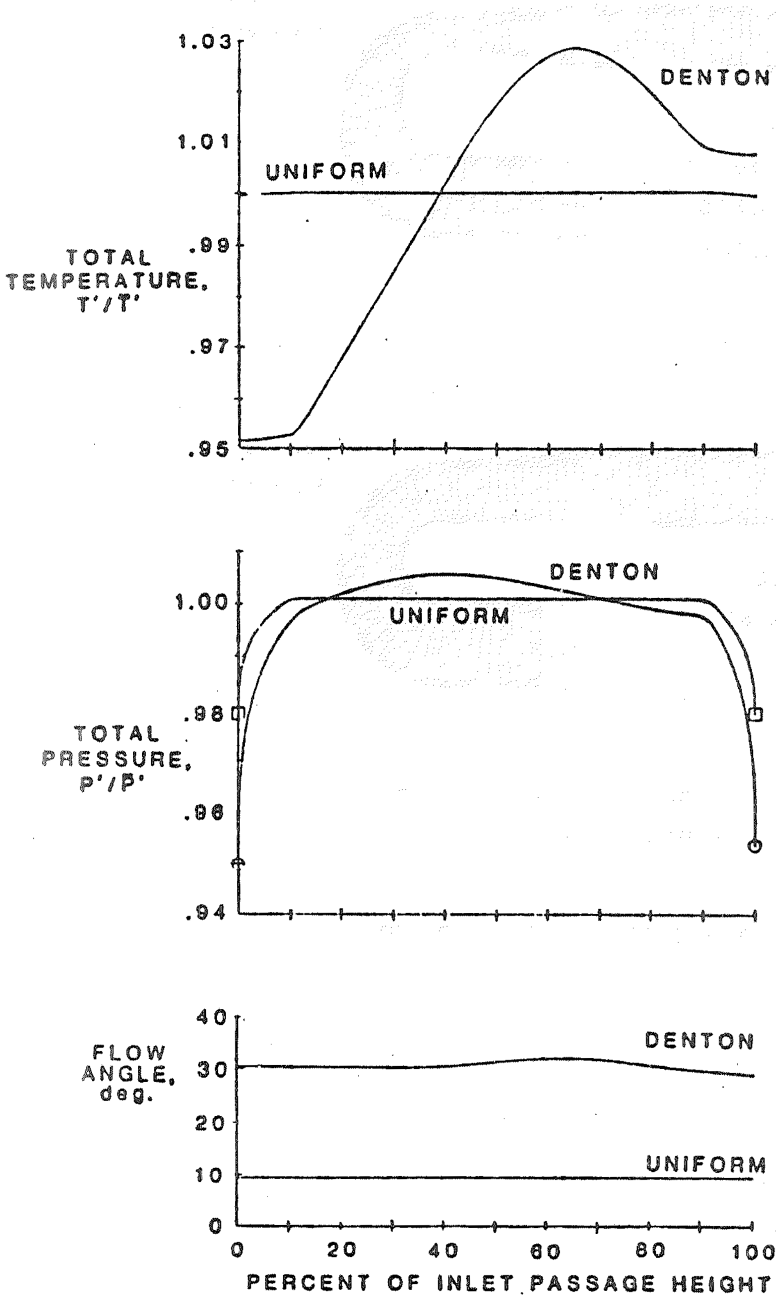
TURNAROUND DUCT GEOMETRIES



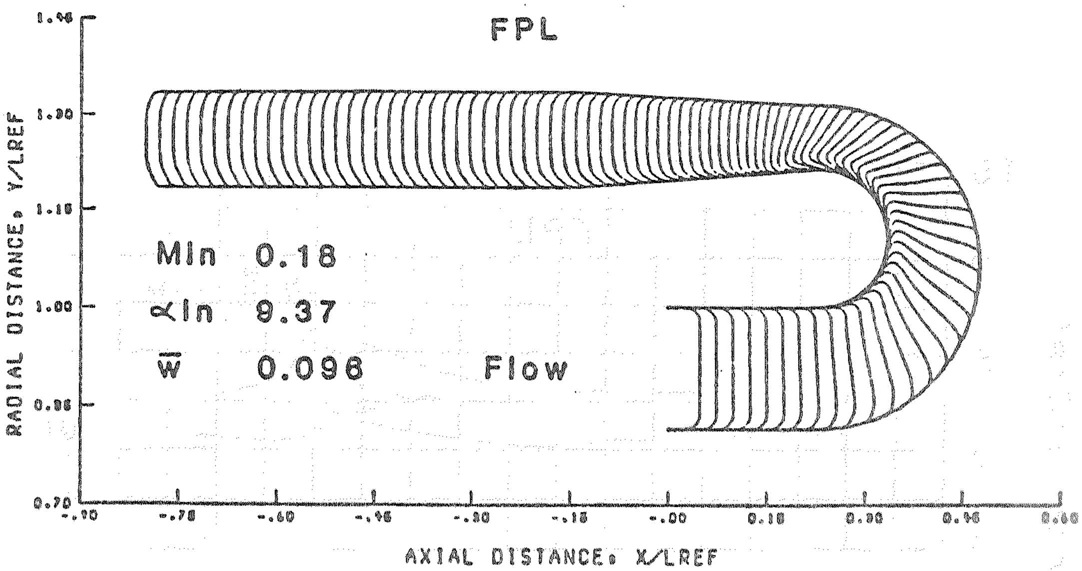
TAD DESIGN INLET CONDITIONS

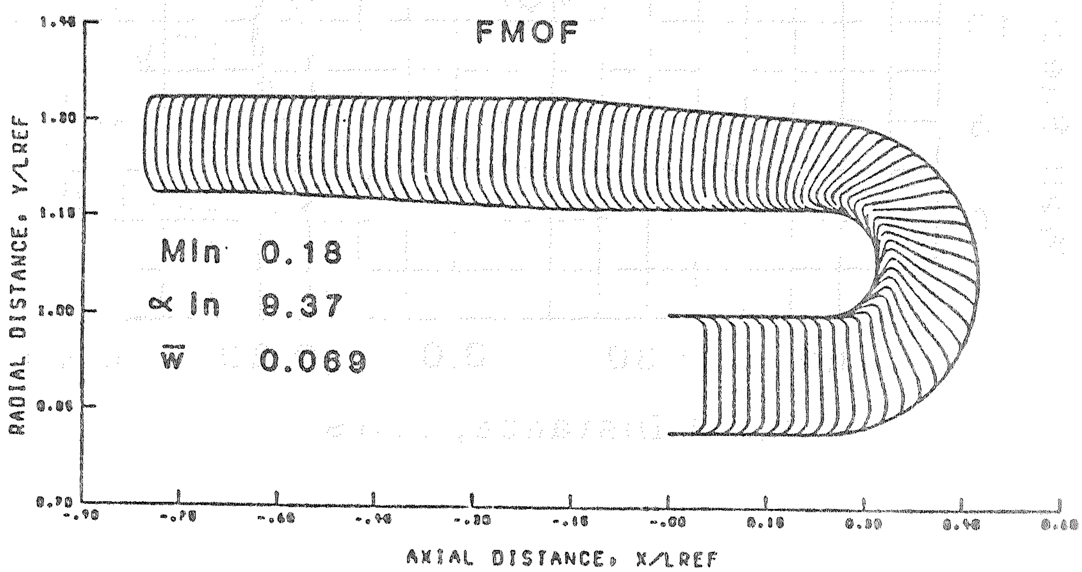
	SSME	STUDY
Fluid	Steam + H_2	Air
Temperature, °R	1761.7	1761.7
Pressure, Atm	250	134.4
Reynolds Number	3.3 X 10^6	3.3 X 10^6
Mach Number	0.18	0.18
Swirl Angle, Deg.	9.37	9.37

TAD INLET FLOW PROFILES

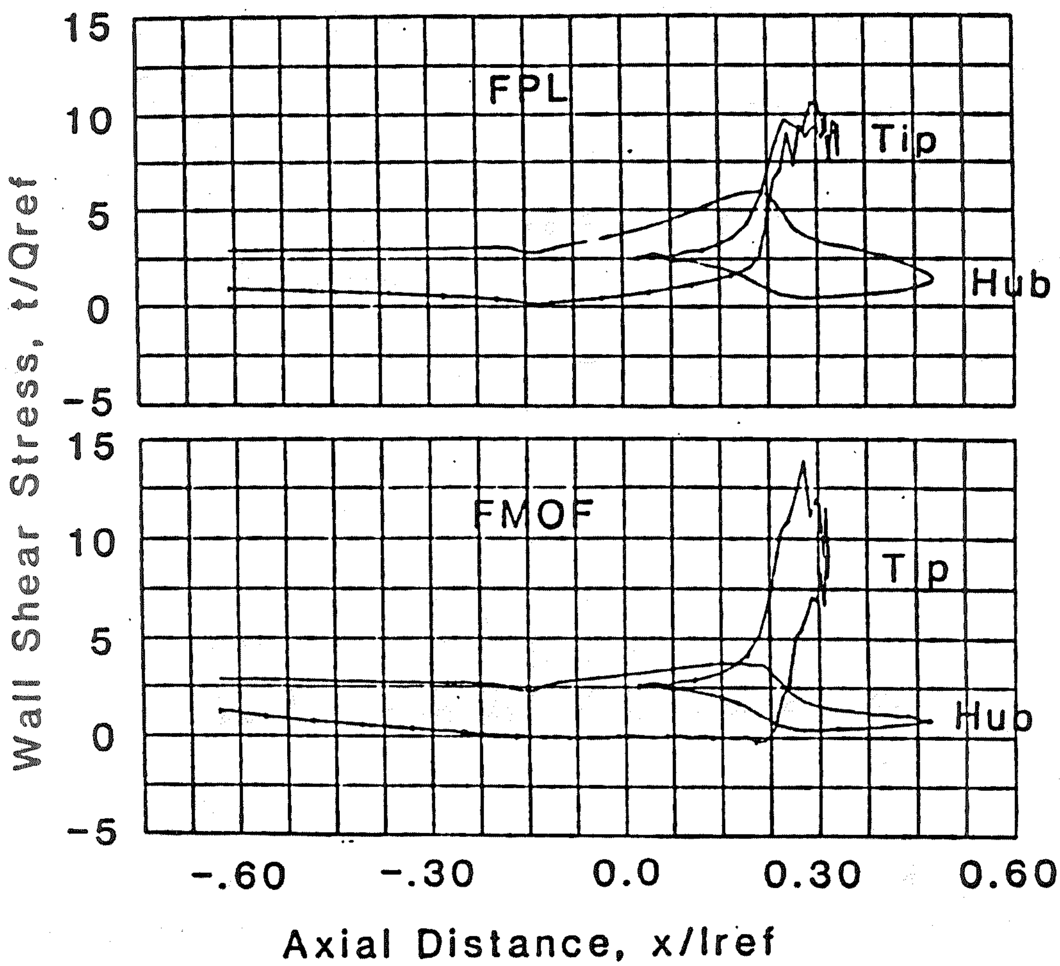


RESULTS FOR UNIFORM INLET

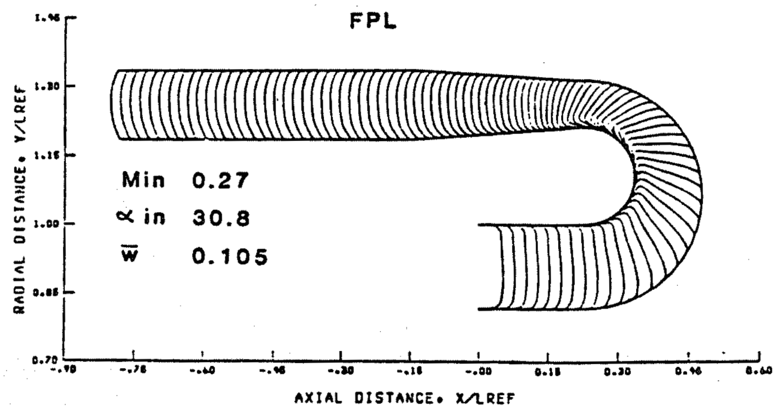


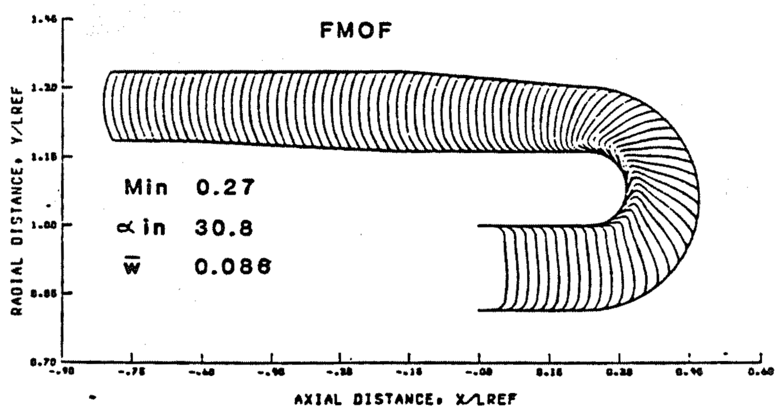


TAD WALL SHEAR STRESSES

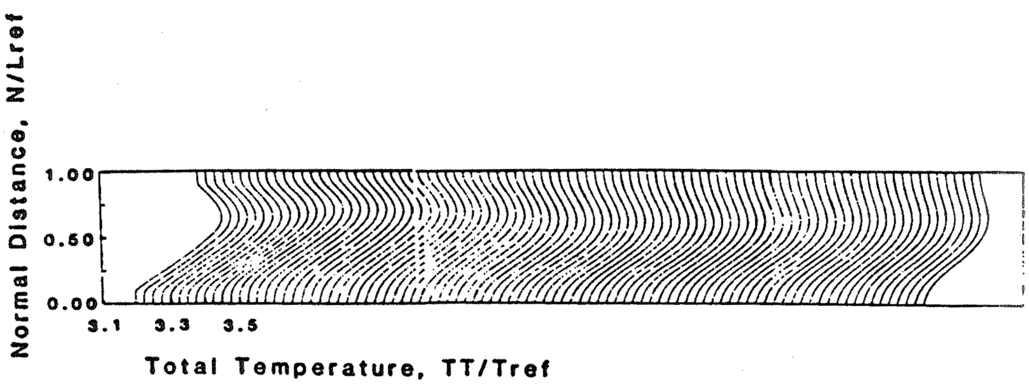


RESULTS FOR DISTORTED INLET

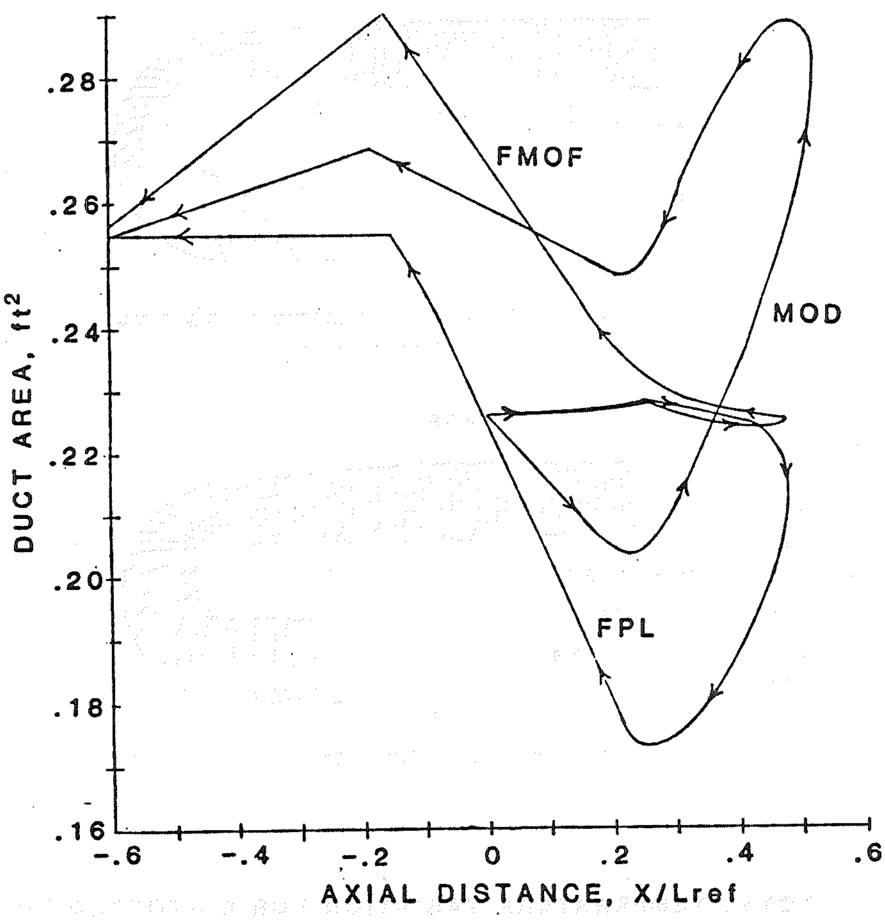




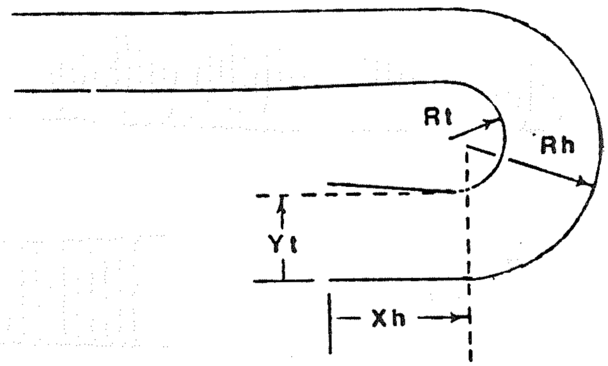
TOTAL TEMPERATURE VARIATION FOR DISTORTED INLET

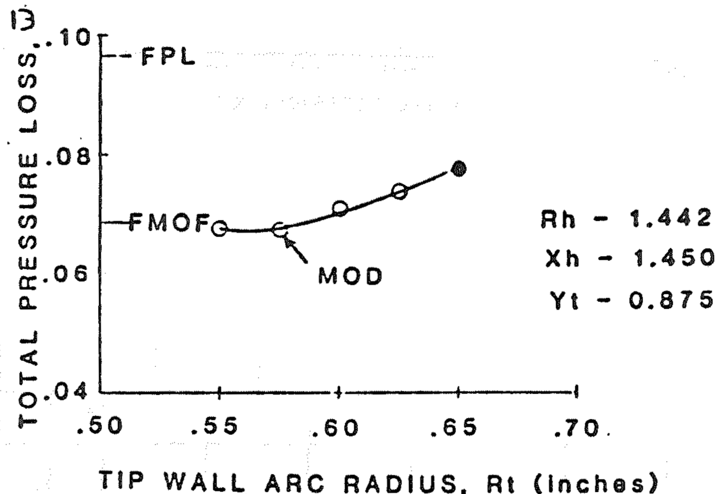


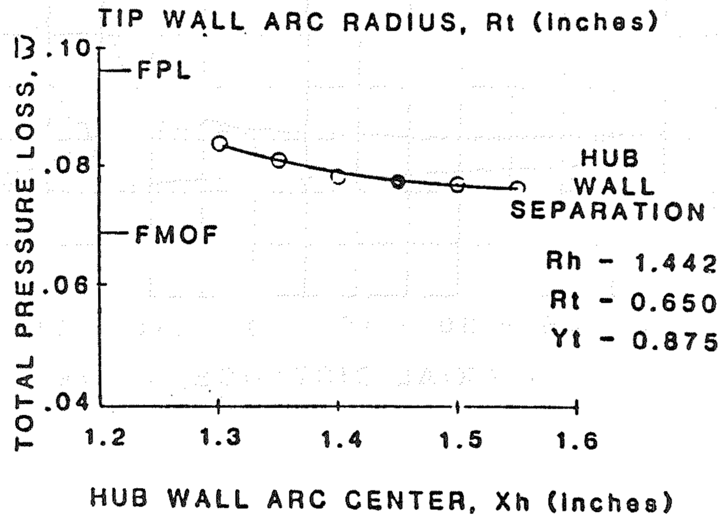
TAD FLOW AREA DISTRIBUTIONS



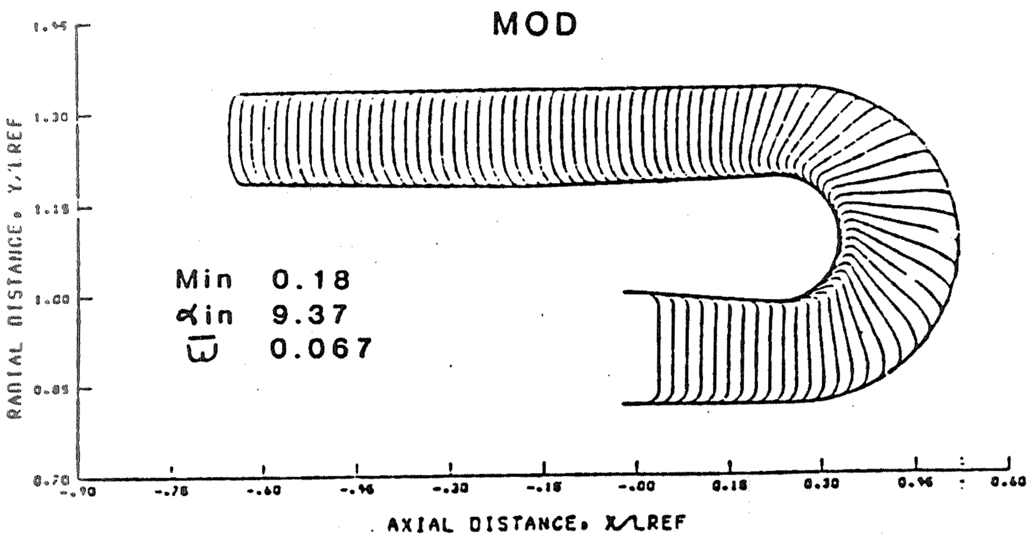
TAD GEOMETRY STUDY

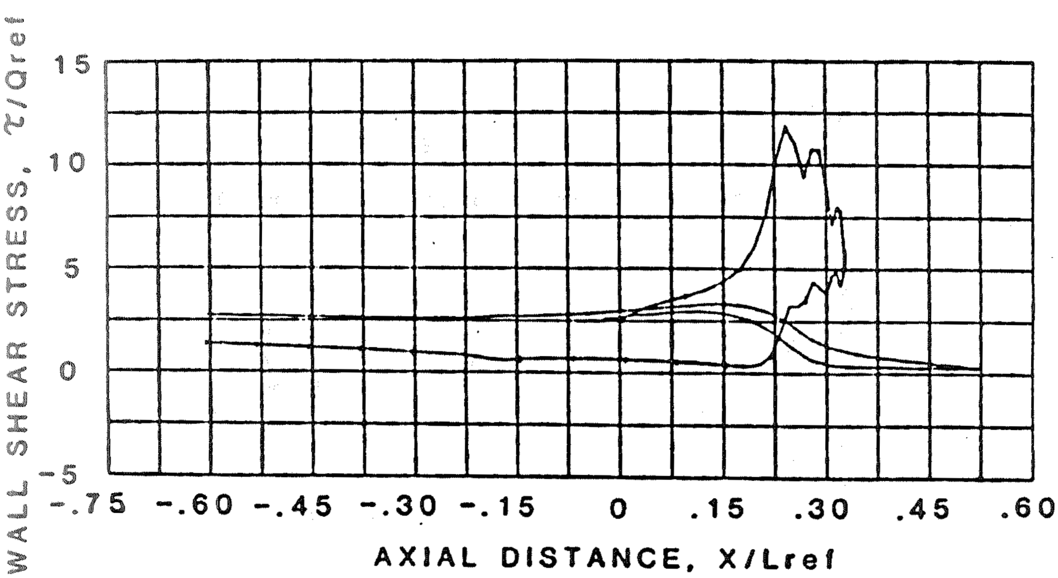


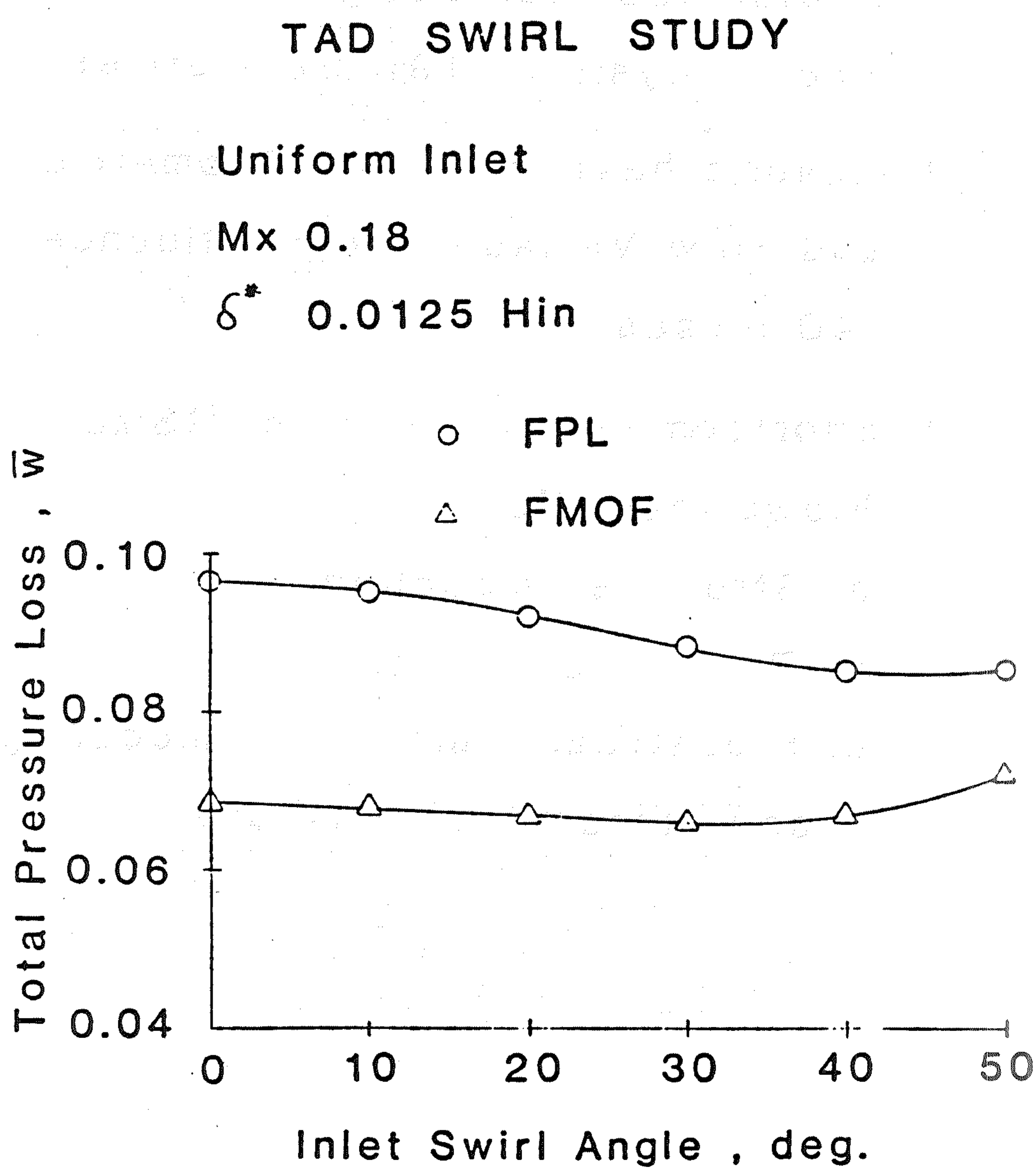




GEOMETRY STUDY RESULTS






TAD SWIRL STUDY
Uniform Inlet
Mx 0.18
δ* 0.0125 Hin
FPL
FMOF
Total Pressure Loss , w̄
0.10
0.08
0.06
0.04
0
10
20
30
40
50
Inlet Swirl Angle , deg.

CONCLUDING REMARKS

1. Useful Code for Design and Analysis of TAD Geometries
2. Results have Indicated Geometric and Flow Variables that Influence TAD losses
3. Shortcomings of Code for SSME Flows Identified
   a. Strut loss modeling
   b. Real fluid effects
   c. Freestream Turbulence modeling and streamline curvature