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A Numerical Investigation of Supersonic Flow Around Aft Bodies

by George C. Catalano and Walter B. Sturek

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Abstract

A numerical investigation has been made for supersonic flow past a cylindrical aft body with and without base bleed and a cylindrical boat tail. Comparison was made to available experimental data. The effect of grid cell density and turbulence models were examined. The calculation of the base flow region was much more highly dependent on grid density that was the forebody or outer flow field. Agreement between the numerical and experimental results improved with the inclusion of the base bleed.

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A NUMERICAL INVESTIGATION OF SUPERSONIC FLOW PAST AN AFT BODY

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ABSTRACT[1]

A numerical investigation has been made for supersonic flow past a cylindrical aft body with and without base bleed and a cylindrical boat tail. Comparison was made to available experimental data. The effect of grid cell density and turbulence models were examined. The calculation of the base flow region was much more highly dependent on grid density than was the forebody or outer flow field. Agreement between the numerical and experimental results improved with the inclusion of the base bleed.

INTRODUCTION

This work reports initial results of a study that examined the application of commercial Computational Fluid Dynamics (CFD) codes to predict high-speed aerodynamic flow fields of interest to the U.S. Army Research Laboratory. The particular aerodynamic problem of interest consists of supersonic flow past an aftbody of a projectile with base mass injection. The flow field is highly compressible and can be considered axisymmetric. The commercial code *Fluent* is used; of particular interest is the careful characterization of the various turbulence models employed in the CFD code.

REVIEW OF PREVIOUS WORK

One of the most important parameters in the design of a projectile is the total aerodynamic drag, which consists of three components: the pressure or wave drag, the viscous or boundary layer drag, and the base drag. Base drag, which can dominate the other two types of drag, has been historically difficult to predict.

Over the past several years, the ability to compute the base flow region has advanced. Sahu, Nietubicz and Steger (1) examined projectile base flow with and without base flow injection using Navier-Stokes computations.

Sahu (2-3) performed further calculations of supersonic flow over a missile aft-body containing an exhaust jet and examined the transonic critical aerodynamic behavior. Sahu and Heavey (4) compared the results of their computational study to experimental data and found the standard k-ε turbulence model performed better in the near wake region than did the algebraic model.

EXPERIMENTAL SETUP

An experimental effort (5) consisting of a detailed laser Doppler velocimeter, a particle image velocimeter and surface pressure measurements has been made in axisymmetric and planar subsonic and supersonic flows with embedded separated regions. The work has concentrated in part on the following essential issues:

- supersonic base flow in the near wake of a cylindrical aft body,
- boat tailing effects on axisymmetric bodies,
- effects of rapid expansion on the development of compressible free shear layers,
- subsonic base cavity flow field structure,
- base bleed with a cylindrical aft body in supersonic flow,
- turbulent structures in a supersonic base flow with base bleed,
- turbulence structure of reattaching axisymmetric free shear layers, and
- shock separated free shear layers.

This work seeks to predict numerically similar flow fields and to address areas of agreement and disagreement.

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The flow field investigated is a blunt cylindrical body with base bleed aligned in a supersonic flow (Figure 1). The supersonic free stream expands as it turns the corner, while the turbulent boundary layer separates and then undergoes recompression, realignment, and redevelopment in the wake of the aft body (5). Fluid from the region adjacent to the base is entrained and accelerated by the outer shear layer and then returned to the base region by a recompression shock system. This region is referred to as the primary recirculation region. Introducing the base bleed, the primary recirculation region is moved downstream of the aft body with a forward stagnation point created, dependent upon the relative strength of the bleed jet and the recirculation region. Experiments performed by several investigators (see [5] for a detailed list) have demonstrated the important effect of such a shift in the location of the primary recirculation region—a change in the base pressure ratio and as a result a change in the aftbody drag. Base bleed is then an effective mechanism for reducing aft body drag. The experimental flow conditions and geometry are shown in Table 1.

FLOW PROPERTY & GEOMETRY	MAGNITUDE
Free Stream Static Pressure	28,700 Pa
Approach Free Stream Mach Number	2.47
Tunnel Stagnation Temperature	300 K
Bleed Flow Mass Flow Rate Ratio	0.01
Base Radius	0.3175 m
Bleed Orifice Radius	0.127 m
Bleed Flow Stagnation Temperature	300 K
Tunnel Stagnation Temperature	470,000 Pa

Table 1. Experimental Flow Conditions and Geometry

COMPUTATIONAL GRID

Gambit (6), a single, integrated preprocessor for CFD analysis, was used for geometry construction and import. In addition, it is used for mesh generation with the capability to produce both structured and unstructured hexahedral, tetrahedral, pyramid, and prism computational cells. Mesh quality examination as well as boundary zone assignment capability is also provided.

For this investigation, the flow field is modeled as an axisymmetric flow past a cylindrical aft body with no swirl. A superimposed boundary layer thickness was matched at the trailing edge of the aft body based on existing experimental data.

It was important to determine the effect of mesh density on the computational results. The number of cells used varied from 7000 to 70,000, thus providing an order of magnitude of difference in this parameter.

Modifications to the grid were incorporated in order to model the cylindrical boat tail. The boat tail geometry is based upon the experimental model of Herrin and Dutton (7). The boat tail for this investigation has a conical shape with an angle relative to the horizontal of 5 degrees and is 31.75 mm (0.5 calibers) in length. The 5-degree angle has been shown to be near the optimal angle from previous investigations (8).

COMPUTATIONAL MODELS

Three different turbulence models (9) are used in the present investigation: the Spalart-Allmaras 1 equation model, the standard k-ε 2 equation model, and the Reynolds stress 5 equation model.

In turbulence models that employ the Boussinesq approach, the central issue is how the eddy viscosity is computed. The model proposed by Spalart-Allmaras solves a transport equation for a quantity that is a modified form of the turbulent kinematic viscosity.

The standard k-epsilon model is a semi-empirical model based on model transport equations for the turbulent kinetic energy, k, and its dissipation rate, ε. The model transport equation for k is derived from the exact equation; however, the model transport equation for ε was obtained using physical reasoning and bears little resemblance to its mathematical counterpart. For this model, the flow is assumed fully turbulent, and the effects of molecular viscosity are negligible.

The Reynolds stress model (RSM) is the most elaborate turbulence model that *Fluent* provides.

Abandoning the isentropic eddy viscosity hypothesis, the RSM closes the Reynolds-averaged Navier-Stokes equations by solving transport equations for the Reynolds stresses, together with an equation for the dissipation rate. This means that four additional transport equations are required in 2-D flows and seven additional transport equations in 3-D flows.

COMPARISON WITH VARYING GRID DENSITY

Results are described for various flow field properties for a given turbulence model (in all cases shown, the RSM) for varying grid density or number of cells within the grid volume. The streamwise mean velocity isocontours are presented in Figure 2 and the turbulent kinetic energy iso-contours are presented in Figure 3, both for the mass bleed ratio of 0.01. For the mean velocity, the isocontours are nearly identical for differing grid densities, while the turbulent kinetic energy results are much different, particularly in the near wake region.

Though not shown here, similar results for the other two turbulence models exist; that is, the mean flow isocontours remain unchanged as a function of grid density, while the turbulent flow results vary significantly.

COMPARISON WITH VARYING TURBULENCE MODELS

For the results shown, the highest value of grid cell density was used. In Figure 4, the streamwise mean velocity contours are compared for two different turbulence models. Using the more detailed RSM results in an elongated wake region near the base. Thus, increasing the complexity of the model seems to result in the same effect as increasing the grid density. Though not shown here, for the case of the radial velocity isocontours, the radial velocity gradient is greatest for the Spalart-Allmaras model and the least for the RSM. Similarly, the static pressure isocontours exhibit higher gradients for the Spalart-Allmaras model compared to the RSM.

COMPARISON WITH EXPERIMENTAL DATA

Comparisons are made in Figures 5-12 with experimental data for supersonic flow past a cylindrical aft body with and without base bleed as well as with and without boat tailing (4,10). For all results shown, the RSM was employed at the largest value of grid cell density. For the cases involving base bleed, the flow exited the aft body parallel to the free stream with the base bleed injection rate (I) was equal to 0.01 times the mass flux injection rate if the entire base served as the exit area for the nozzle. The velocity of the base bleed is considered constant over the exit plane.

- No Base Bleed (I = 0.00)

Figure 5 shows streamwise mean velocity profiles. The nondimensionalized mean velocity (U/Ufs) is plotted vs nondimensionalized radial location (r/R) at different downstream locations (x/D =1.26, 1.42, and 1.73.) Agreement is acceptable, but the numerical model consistently overestimates the extent of the mean wake region and thus overestimates the magnitude of the mean velocity gradient.

Figure 6 shows nondimensionalized turbulent shear stress (-uv/Ufs^2) profiles at different downstream locations (x/D =1.26, 1.42, and 1.73). The numerical results underestimate the maximum value of the turbulent shear stresses and underestimate the extent of the turbulent velocity field. This is the opposite of what was seen in the mean velocity field.

Figure 7 compares base pressure over the length of the entire base with acceptable agreement between numerical and experimental results.

- Base Bleed (I = 0.01)

Figure 8 presents streamwise mean velocity profiles. The nondimensionalized mean velocity (U/Ufs) is plotted vs a nondimensionalized radial location (r/R) at different downstream locations (x/D = 0.95, 1.26, 1.95, and 2.04). The results are much closer to the experimental data (4), suggesting that the numerical model more accurately predicts the important flow features in the case of base bleed.

Figure 9 presents turbulent kinetic energy profiles. The nondimensionalized kinetic energy (k/Ufs^2) is plotted vs nondimensionalized radial location (r/R) at different downstream locations (x/D = 0.95, 1.26, 1.95, and 2.04) with an acceptable level of agreement between numerical and experimental results.

Similarly, nondimensionalized turbulent stress (-uv/Ufs^2) profiles also demonstrate acceptable agreement at different downstream locations (x/D = 0.95, 1.26, 1.95, and 2.04).

Figure10 shows the downstream development of the streamwise mean velocity. The magnitudes are quite close in agreement between the numerical and experimental results, as is the location of the zero mean velocity or leading edge of the recirculation region.

- Aft Body Boat Tailing with and without Base Bleed (I = 0.00 & I = 0.01)

Streamwise mean velocity (U/Ufs) and turbulent kinetic energy (k/Ufs^2), as functions of downstream location (x/R) are shown in Figures 11-12. Agreement between numerical and experimental results increases with increasing downstream distance from the exit plane.

SUMMARY

Using the commercial CFD code *Fluent* Version 5.1.1, a numerical investigation has been made for supersonic flow past a cylindrical aft body with and without base bleed and boat tailing. The effects of the grid cell density and the turbulence closure models were each examined. The mean and turbulent velocity fields and pressure fields were all documented.

The grid cell density was found to have its most significant effect on the calculation of the turbulent velocity fields, while the mean velocity field was essentially independent of grid cell density. Three different turbulence closure models were employed with the RSM, providing results most closely aligned with experimental data.

The numerical results were found to be closer to the experimental data for the case of base bleed than they were in the case of no base bleed. The boat tailing did not have an observable effect on the comparison between numerical and experimental data.

ACKNOWLEDGEMENT

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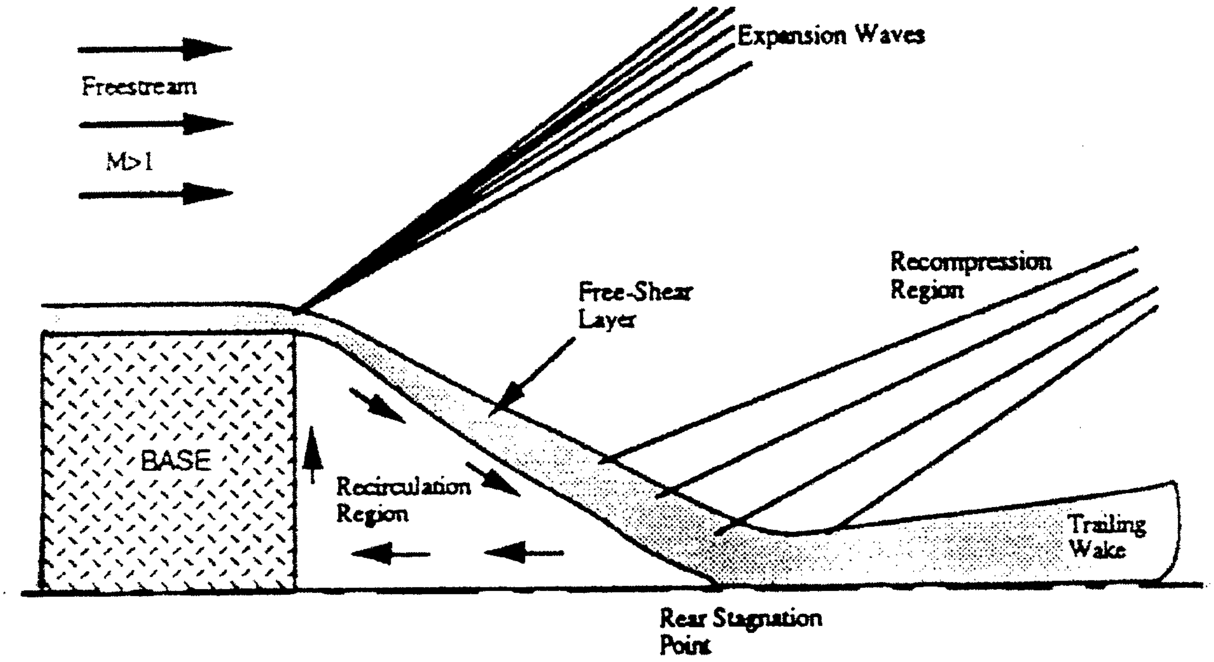

Fig. 1 Schematic diagram of supersonic base flow.

From Reference 5, courtesy of Dr. Craig Dutton.

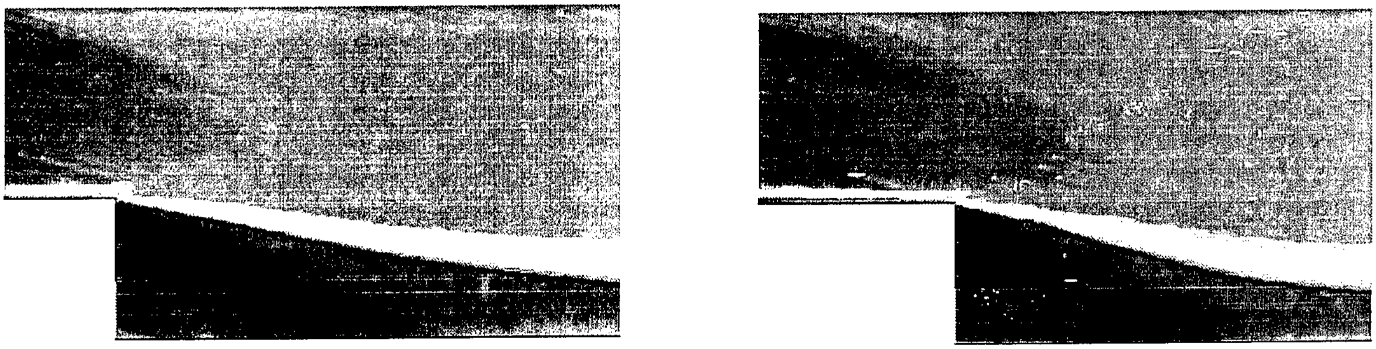

Figure 2. Comparison of Streamwise Mean Velocity Isocontours for High and Low Grid Densitites. High Grid Density (70,000) on Left. Low Grid Density (7000) on Right.

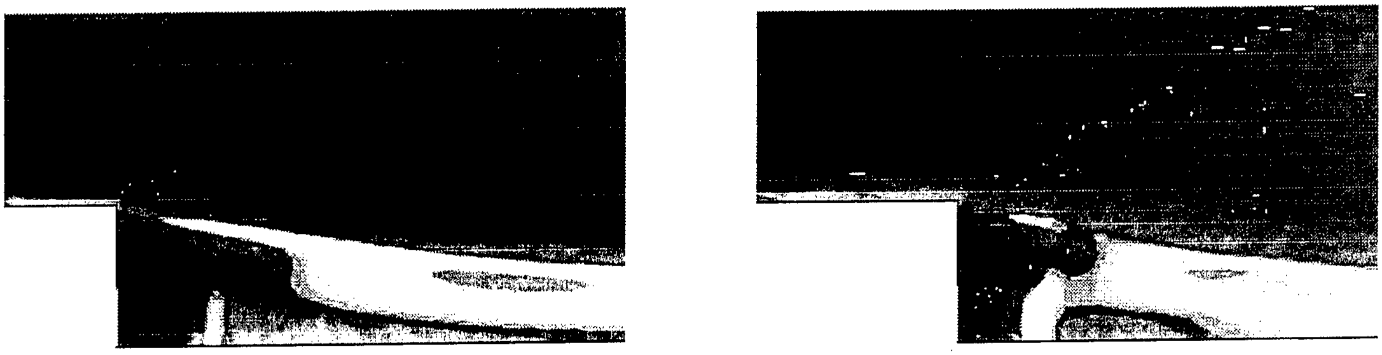

Figure 3. Comparison of Turbulent Kinetic Energy Isocontours for High and Low Grid Densities. High Grid Density (70,000) on Left. Low Grid Density (7000) on Right.

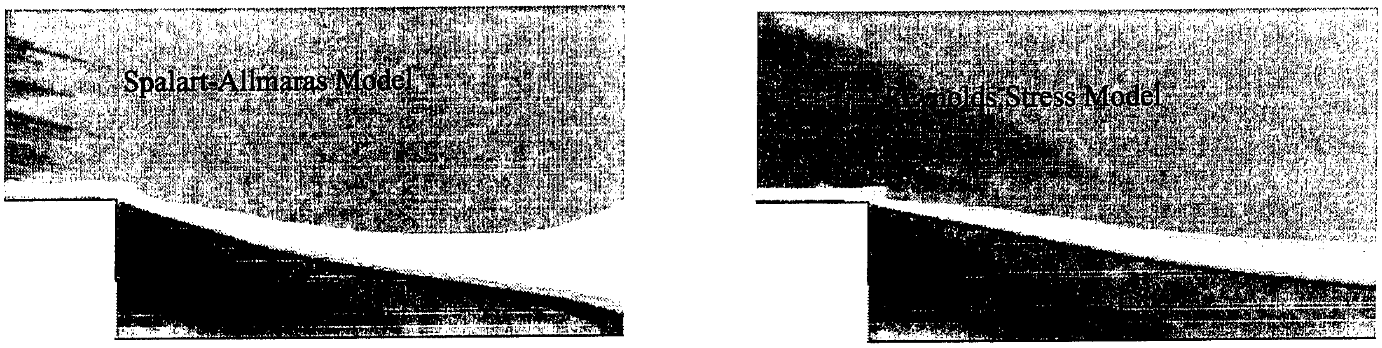

Figure 4. Comparison of Streamwise Mean Velocity Isocontours for Two Turbulence Models. Spalart-Allmaras on Left. Reynolds Stress Model on Right.

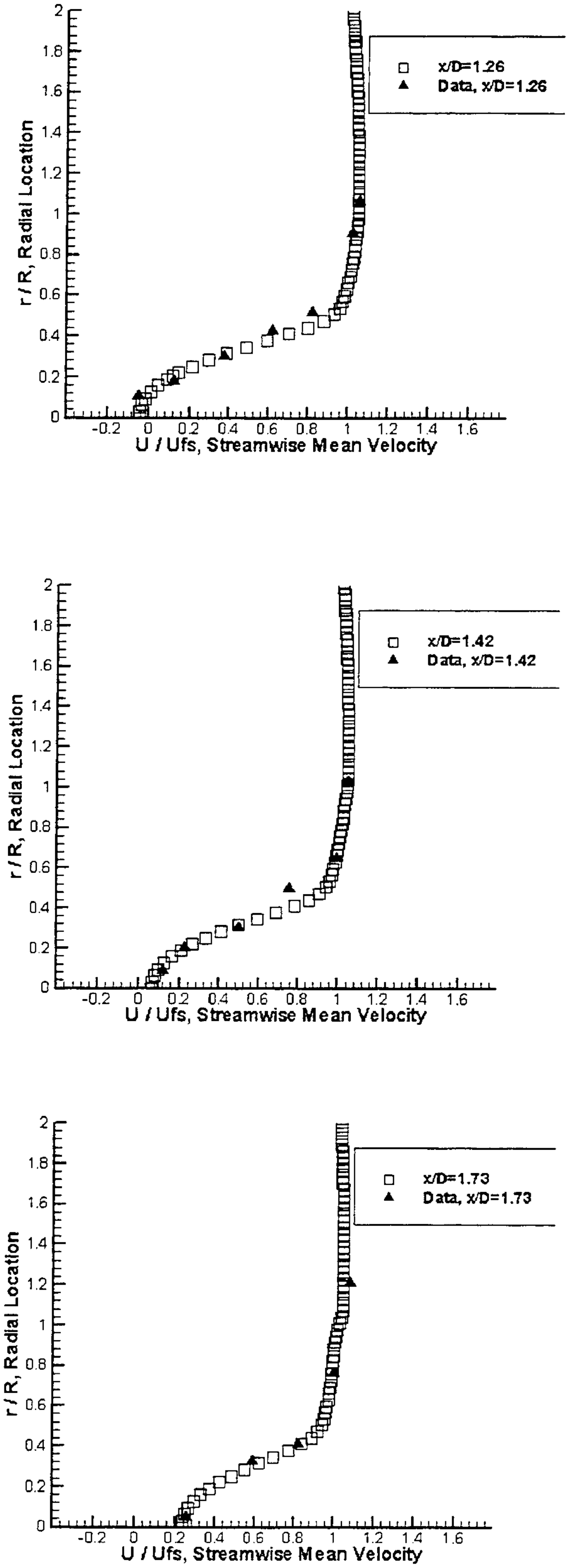

Figure 5. Streamwise Mean Velocity (U/Ufs) Profiles as Function of Radial Position (r/R) for various Downstream Locations Compared to Experimental Data(11) for No Base Bleed (I=0.0).

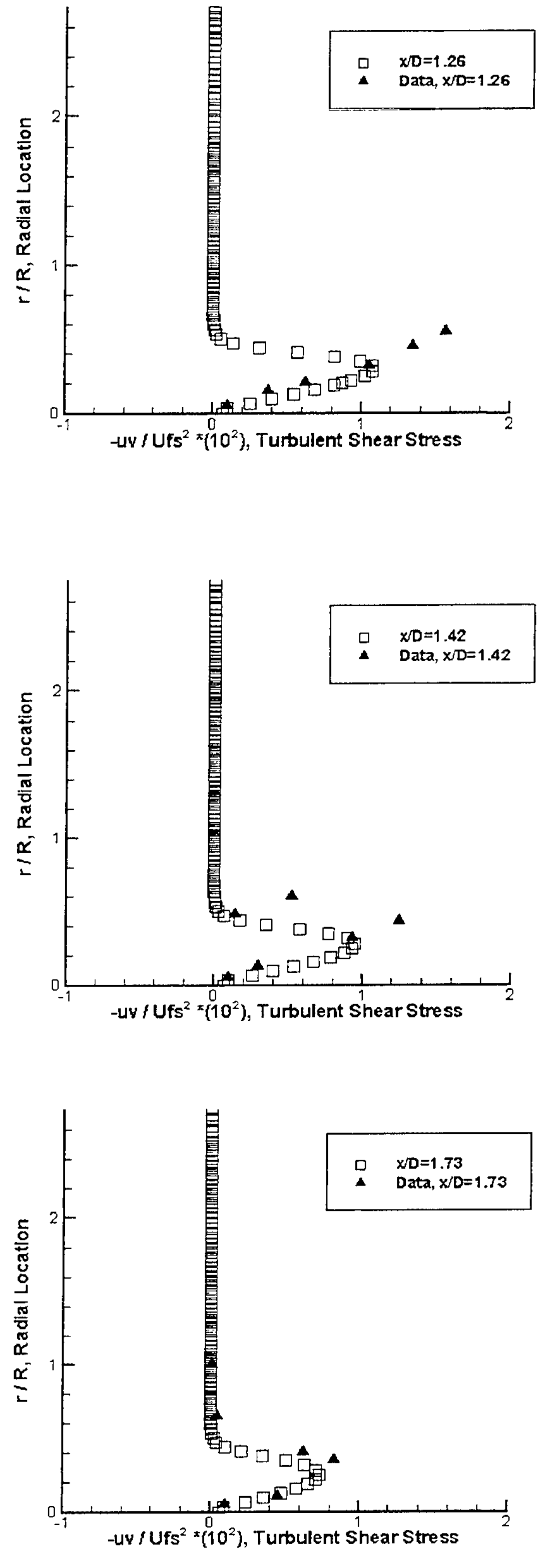

Figure 6. Turbulent Shear Stress (-uv/Ufs^2) as Function of Radial Position (r/R) for Various Downstream Locations Compared to Experimental Data (11) for No Base Bleed (I=0.0).

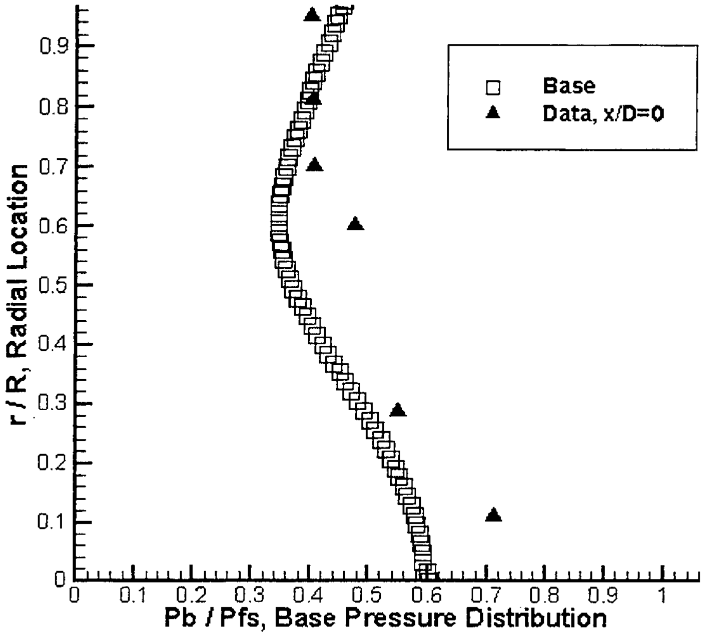

Figure 7. Nondimensionalized Base Pressure Distribution, (Pb/Pfs) vs. Radial Location on Base for No Base Bleed (I=0.0) with Comparison to Experimental Data(11).

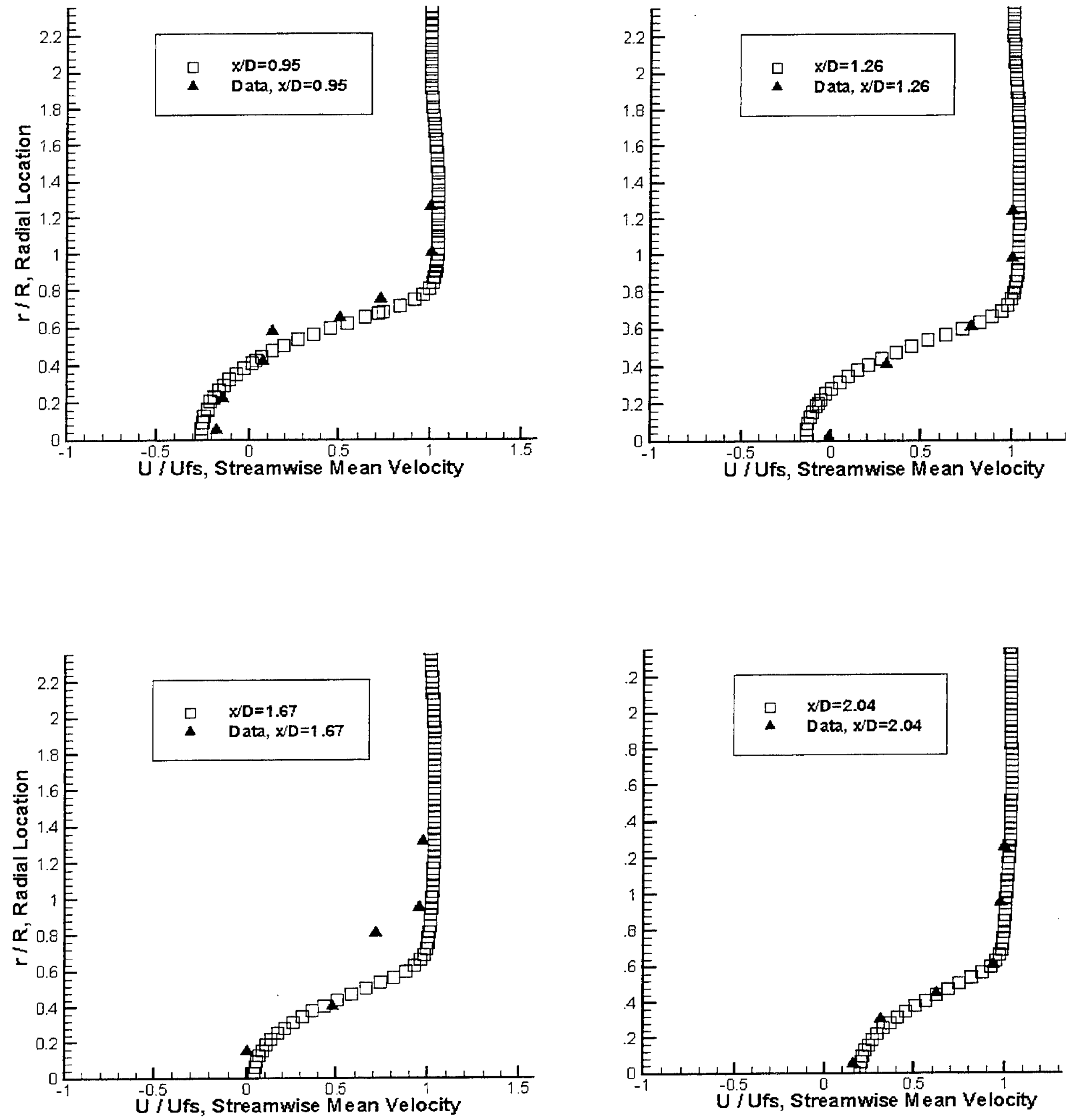

Figure 8. Streamwise Mean Velocity (U/Ufs) Profiles as Function of Radial Position (r/R) for Various Downstream Locations Compared to Experimental Data (4) for Base Bleed (I=0.01).

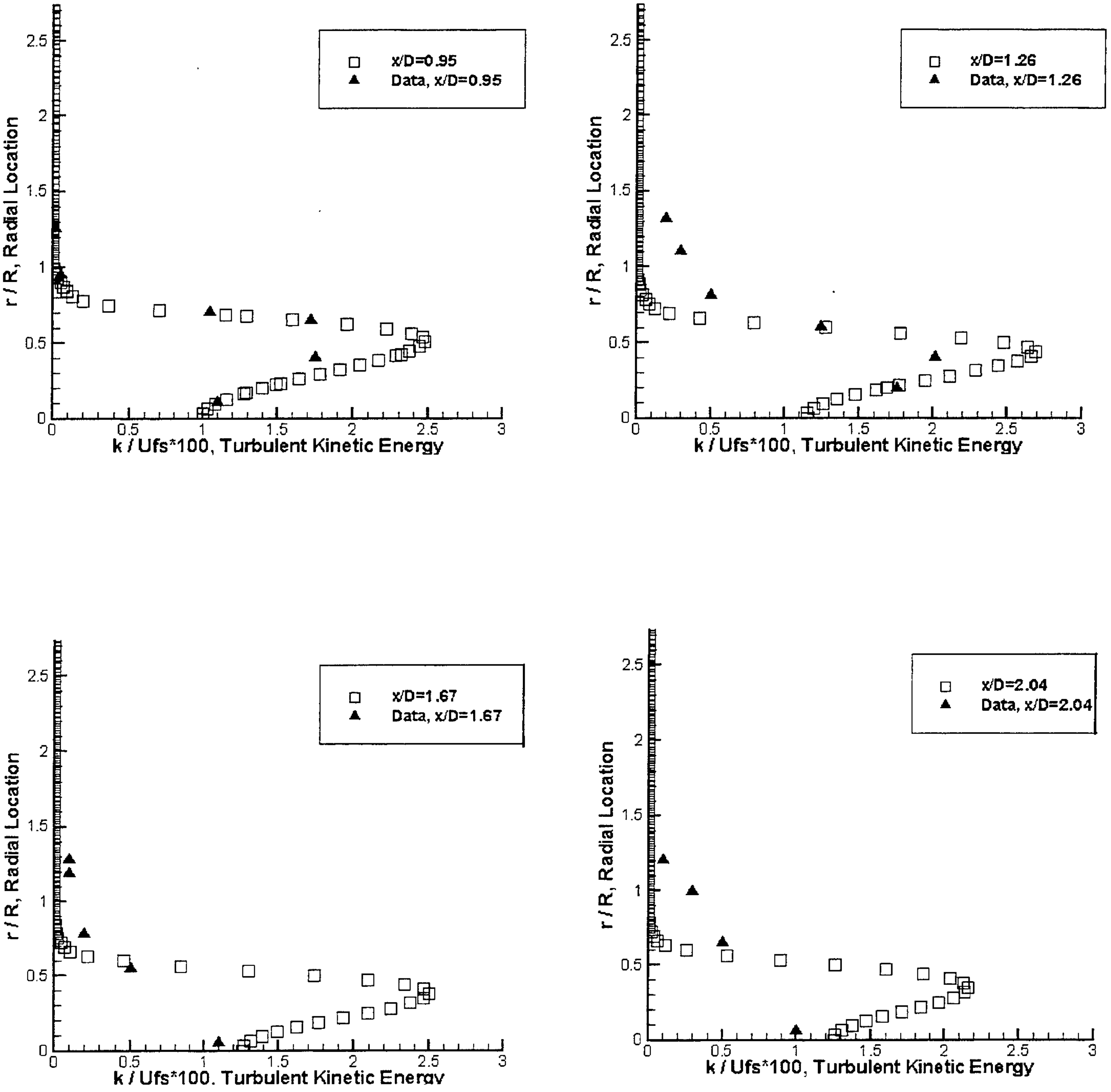

Figure 9. Turbulent Kinetic Energy (k//Ufs) Profiles as Function of Radial Position (r/R) for Various Downstream Locations Compared to Experimental Data (4) for Base Bleed (I=0.01).

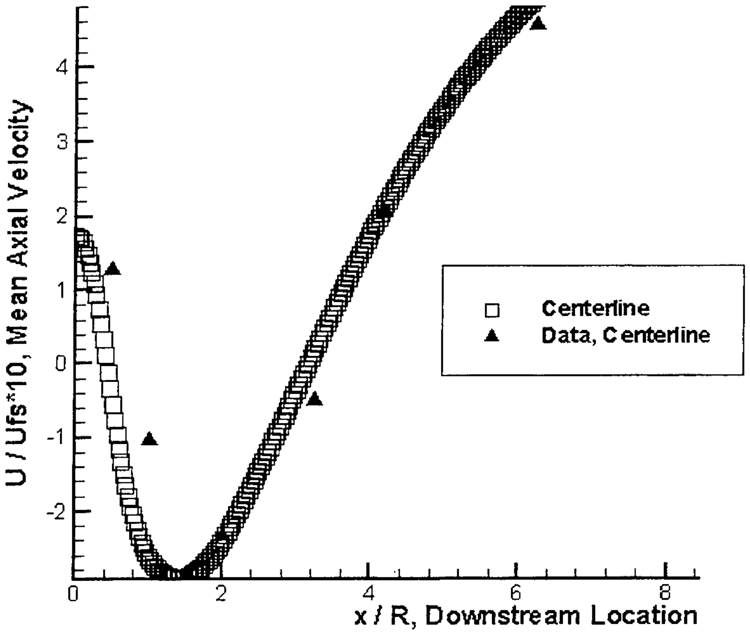

Figure 10. Streamwise Mean Velocity (U/Ufs) vs. Downstream Location (x/D) for Base bleed (I=0.01) Compared to Experimental Data (4).

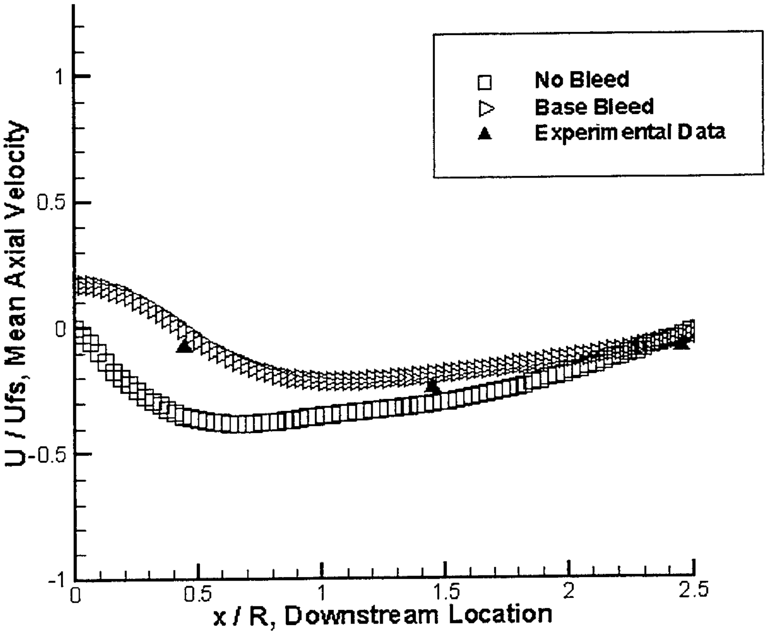

Figure 11. Streamwise Mean Velocity (U/Ufs) as Function of Downstream Location (x/R) for Base bleed (I=0.01) and No Base Bleed Compared to Experimental Data (3).

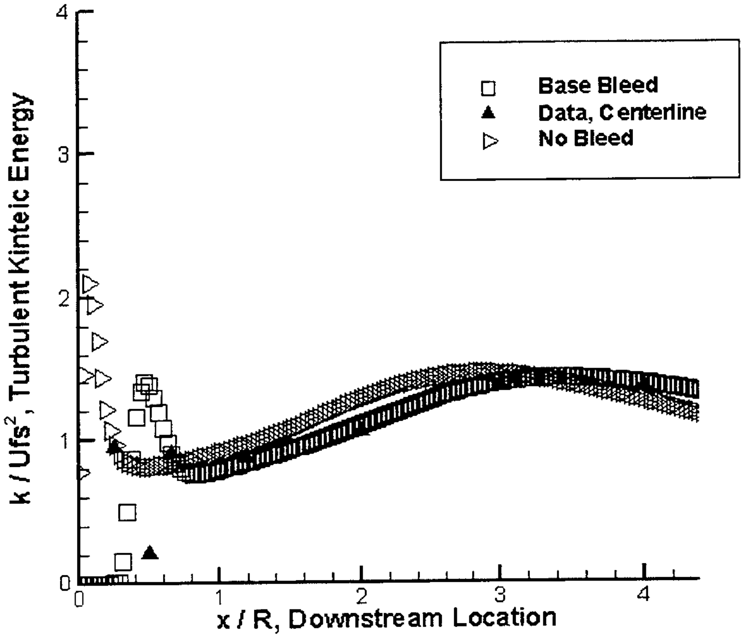

Figure 12. Turbulent Kinetic Energy (k/Ufs^2) vs. Downstream Location (x/R) for Base Bleed (I=0.01) and No Base Bleed Compared to Experimental Data (3).

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13. ABSTRACT *(Maximum 200 words)*

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