N95- 23652

51-34
43711
p. 23

Validation of a Computational Fluid Dynamics (CFD) Code for Supersonic Axisymmetric Base Flow

P. K. Tucker

NASA/Marshall Space Flight Center
Marshall Space Flight Center, AL

Abstract

The ability to accurately and efficiently calculate the flow structure in the base region of bodies of revolution in supersonic flight is a significant step in CFD code validation for applications ranging from base heating for rockets to drag for protectives.

The FDNS code is used to compute such a flow and the results are compared to benchmark quality experimental data. Flowfield calculations are presented for a cylindrical afterbody at M = 2.46 and angle of attack $\alpha = 0$. Grid independent solutions are compared to mean velocity profiles in the separated wake area and downstream of the reattachment point. Additionally, quantities such as turbulent kinetic energy and shear layer growth rates are compared to the data. Finally, the computed base pressures are compared to the measured values. An effort is made to elucidate the role of turbulence models in the flowfield predictions. The level of turbulent eddy viscosity, and its origin, are used to contrast the various turbulence models and compare the results to the experimental data.

Validation of a CFD Code for Supersonic Axisymmetric Afterbody Flow

Kevin Tucker

1993 CFD Conference

OVERVIEW

- Motivation
- Objectives
- Experimental Dataset
- Summary of Cases
- Results
  - Flow Structure
  - Data Comparisons
- Conclusion
  - Summary
  - Future Work

MOTIVATION

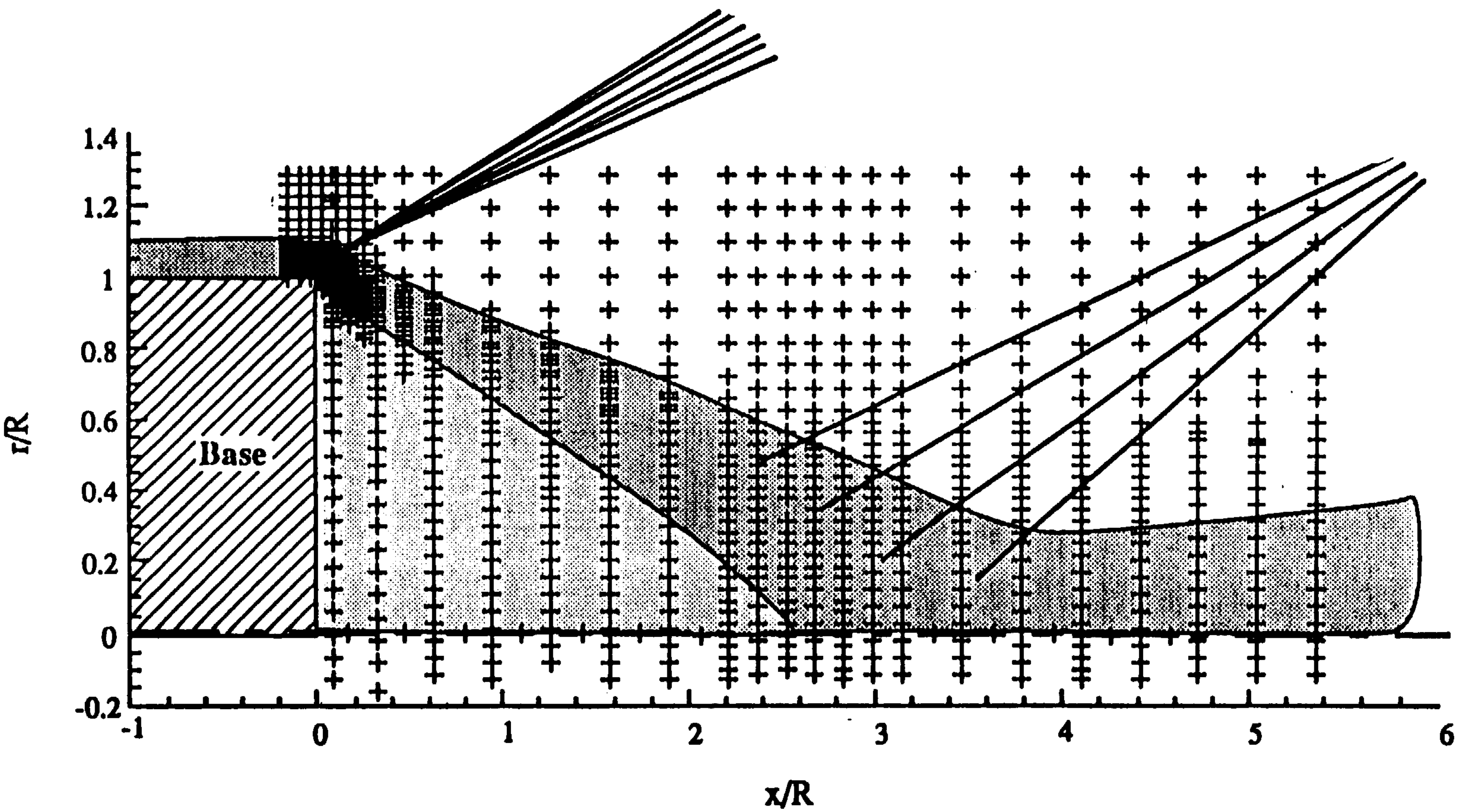
- Stemmed from NLS base heating study
- Need to predict base pressures in recirculating flows
- One step in a building-block validation approach for base flows

OBJECTIVES

- Determine factors which influence base pressure predictions
- Elucidate role of turbulence models for compressible, recirculating flows
- Provide guidance for 3-D base flow calculations

EXPERIMENTAL DATASET

UIUC Supersonic Afterbody (Dutton & Herrin)



EXPERIMENTAL DATASET

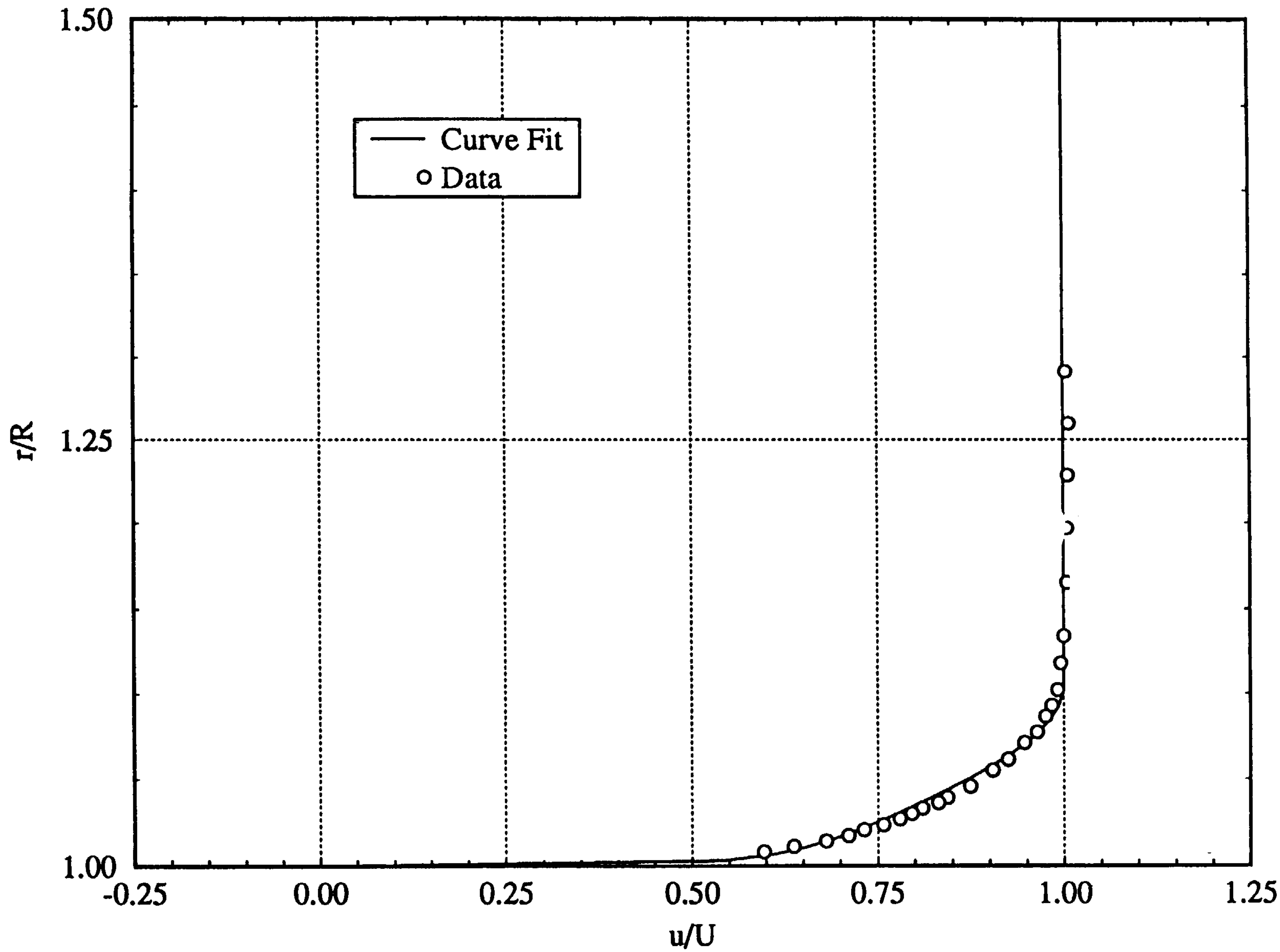
Freestream Properties

- $M=2.46$
- $U=1860.2$ ft/sec
- $P_o=74.7$ psia
- $T_o=532.8$ R
- $Re=1.6$ e+7/ft

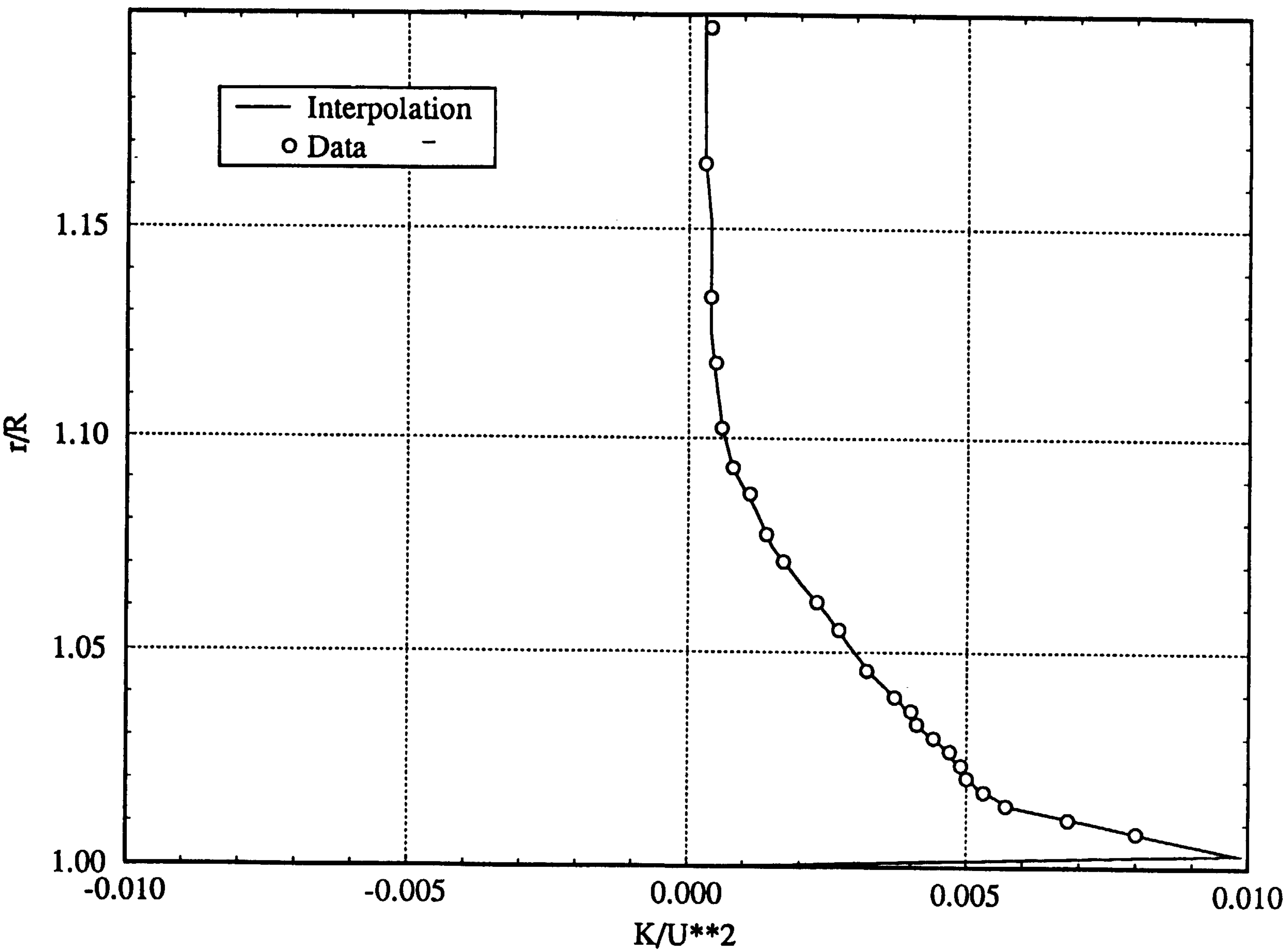
Boundary Layer Profile

- Boundary layer velocity profile-Sun & Childs curve fit for turbulent, compressible boundary layers
- Temperature-recovery factor of 0.89 (Kays & Crawford)
- Pressure-assumed constant static pressure thru boundary layer
- Density-calculated via equation of state
- Turbulent kinetic energy-interpolated from data onto grid

INLET VELOCITY PROFILE



INLET TURBULENT KINETIC ENERGY PROFILE



SUMMARY of CASES/RESULTS

Differencing Scheme	Turbulence Model	Reattachment	Avg. Base Press.
First order upwind	Standard k-e	-0.180	-0.310
First order upwind	Standard k-e, k-corr	0.000	-0.202
First order upwind	Standard k-e, e-corr	0.022	-0.186
First order upwind	Extended k-e	-0.045	-0.218
First order upwind	Extended k-e, k-corr	0.112	-0.140
First order upwind	Extended k-e, e-corr	0.131	-0.128
Second order upwind	Standard k-e, e-corr	0.052	-0.145
Second order upwind	Extended k-e, e-corr	0.191	-0.061
Second order central	Standard k-e, e-corr	0.052	-0.147
Second order central	Extended k-e, e-corr	0.180	-0.065
Third order upwind	**Standard k-e**	**-0.165**	-0.300
Third order upwind	Standard k-e, k-corr	0.034	-0.172
Third order upwind	Standard k-e, e-corr	0.052	-0.147
Third order upwind	Extended k-e	-0.008	-0.186
Third order upwind	**Extended k-e, k-corr**	**0.150**	**-0.087**
Third order upwind	Extended k-e, e-corr	-0.179	-0.065

TURBULENCE MODELS

- Standard k-ε model

$$\frac{\partial \rho k}{\partial t} + \frac{\partial}{x_i}\left(\rho u_i k + \mu_L \frac{\partial k}{\partial x_i}\right) = \rho \ (Pr - \varepsilon)$$

$$\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho u_i \varepsilon + \mu_L \frac{\partial \varepsilon}{\partial x_i}\right) = \rho \frac{\varepsilon}{k} \ (C_1 Pr - C_2 \varepsilon)$$

$$Pr = \frac{\mu_T}{\rho}\left\{\frac{1}{2}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right)^2 - \frac{2}{3}\left(\frac{\partial u_k}{\partial x_k}\right)^2\right\}$$

$$C_1 = 1.43 \quad C_2 = 1.92 \quad S_{C_k} = 1.0 \quad S_{C_\varepsilon} = 1.92$$

5-19714

TURBULENCE MODELS

- **Extended k-ε model**

$$C_1 = 1.15 + 0.25\left(\frac{Pr}{\varepsilon}\right)$$

$$C_2 = 1.90$$

$$S_{c_k} = 0.89$$

$$S_{c_\varepsilon} = 1.15$$

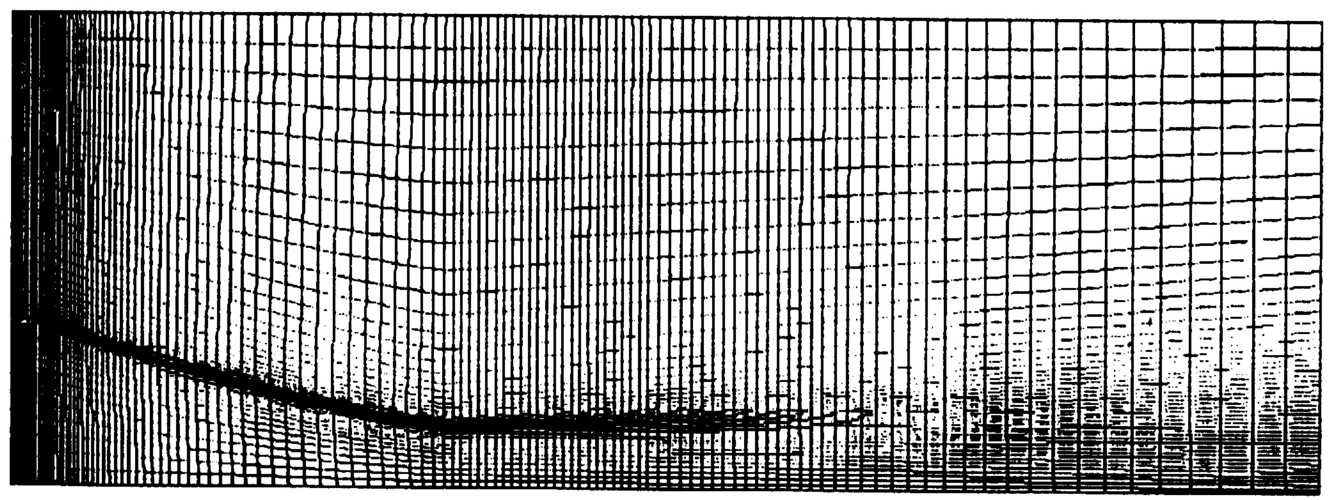
- k-correction

$\varepsilon = \left(1 + M_t^2\right)$ replaces ε in the k-eqn source term

where $M_t^2 = \frac{k}{a^2}$

GRID

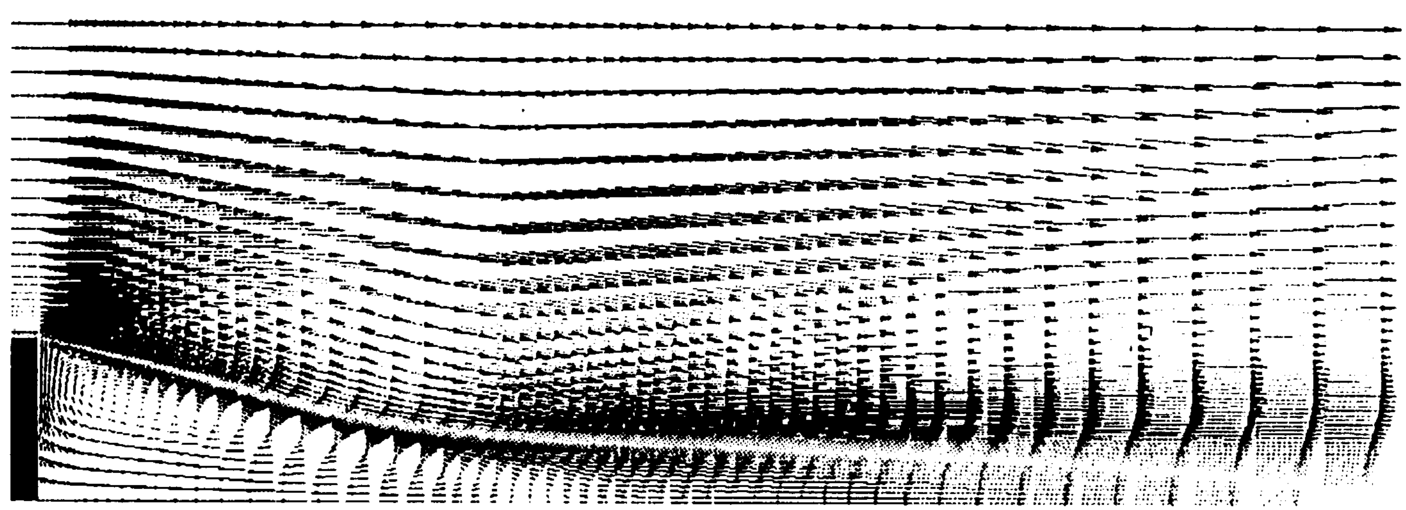
AXISYMMETRIC AFTERBODY



VELOCITY COLORED BY VELOCITY MAGNITUDE

THIRD ORDER UPWIND

EXTENDED ke MODEL; k-CORRECTION



q17.2.img

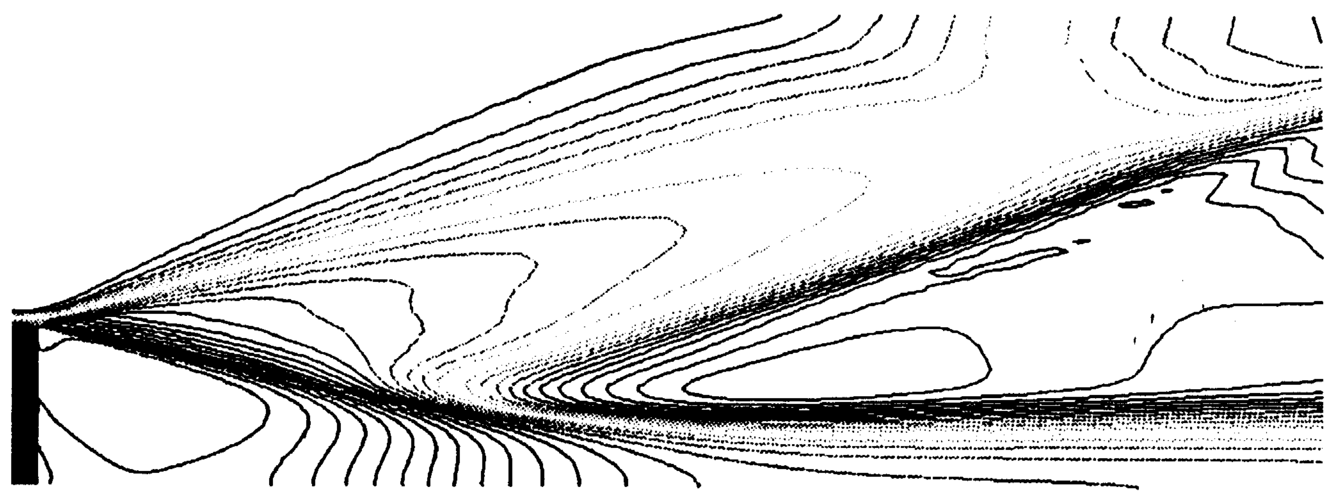
DENSITY (SLUGS/FT**3)

THIRD ORDER UPWIND

EXTENDED ke MODEL; k-CORRECTION

CONTOUR LEVELS
0.000
0.000
0.000
0.000
0.001
0.001
0.001
0.001
0.001
0.001
0.001
0.001
0.001
0.001
0.001
0.001
0.001
0.001
0.001
[illegible]
0.001
0.001
0.001
0.002
0.002
0.002
0.002
0.002
0.002
0.002
0.002
0.002

2.460	MACH
0.00 DEG	ALPHA
$1.63\times10^{**}6$	Re
277x101	GRID



q17.1.img

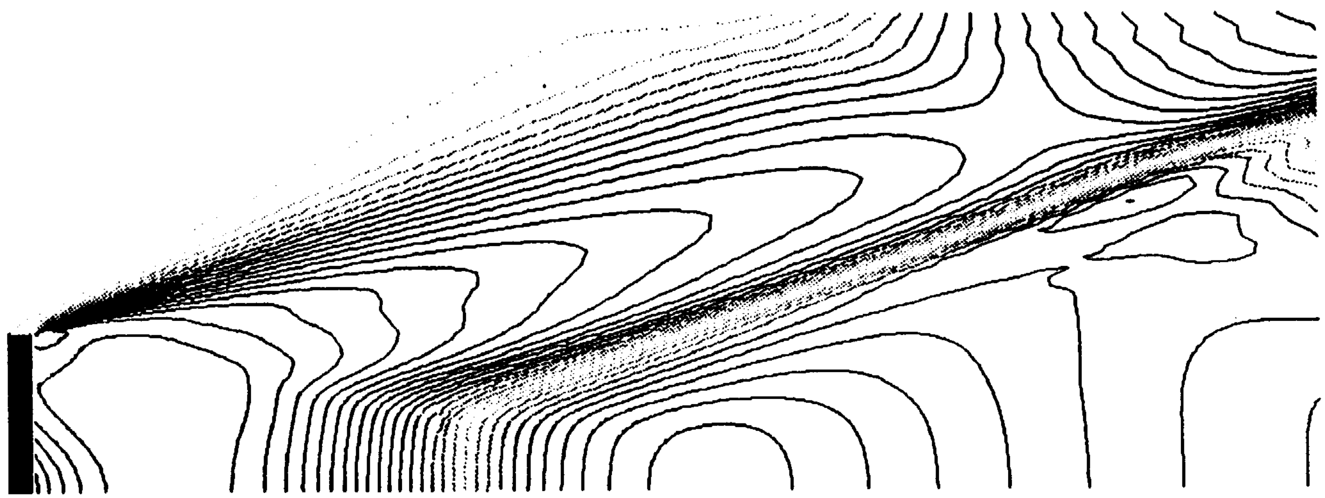
PRESSURE (LB/FT**2)

THIRD ORDER UPWIND

EXTENDED kε MODEL; k-CORRECTION

2.460	MACH
0.00 DEG	ALPHA
1.63x10**6	Re
277x101	GRID

CONTOUR LEVELS
300.0
320.0
340.0
360.0
380.0
400.0
420.0
440.0
460.0
480.0
500.0
520.0
540.0
560.0
580.0
600.0
620.0
640.0
660.0
680.0
700.0
720.0
740.0
760.0
780.0
800.0
820.0
840.0
860.0
880.0



q17.3.img

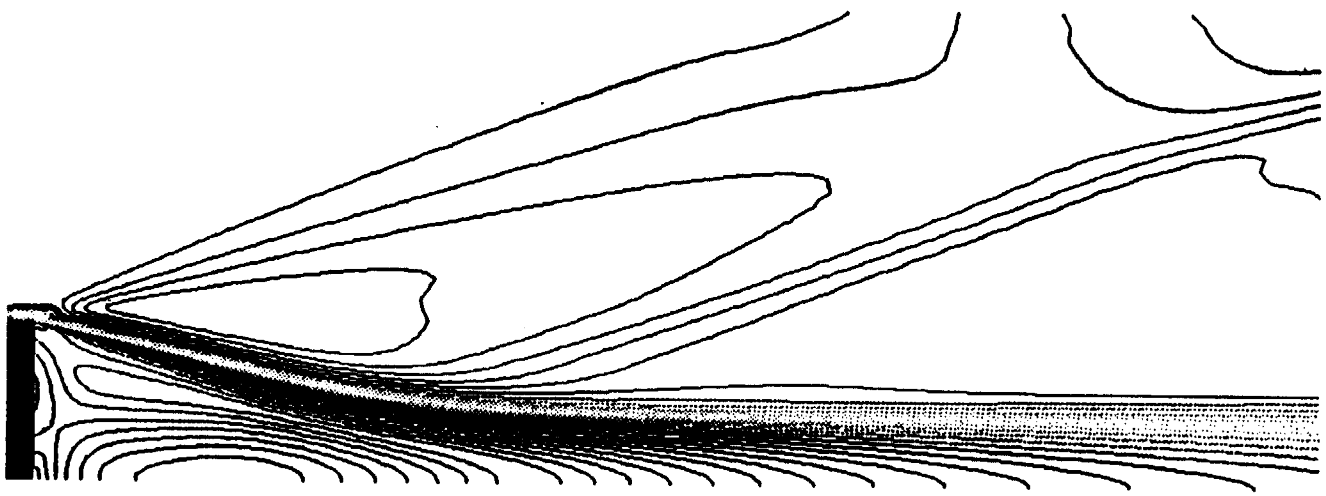
MACH NUMBER

THIRD ORDER UPWIND

EXTENDED ke MODEL; k-CORRECTION

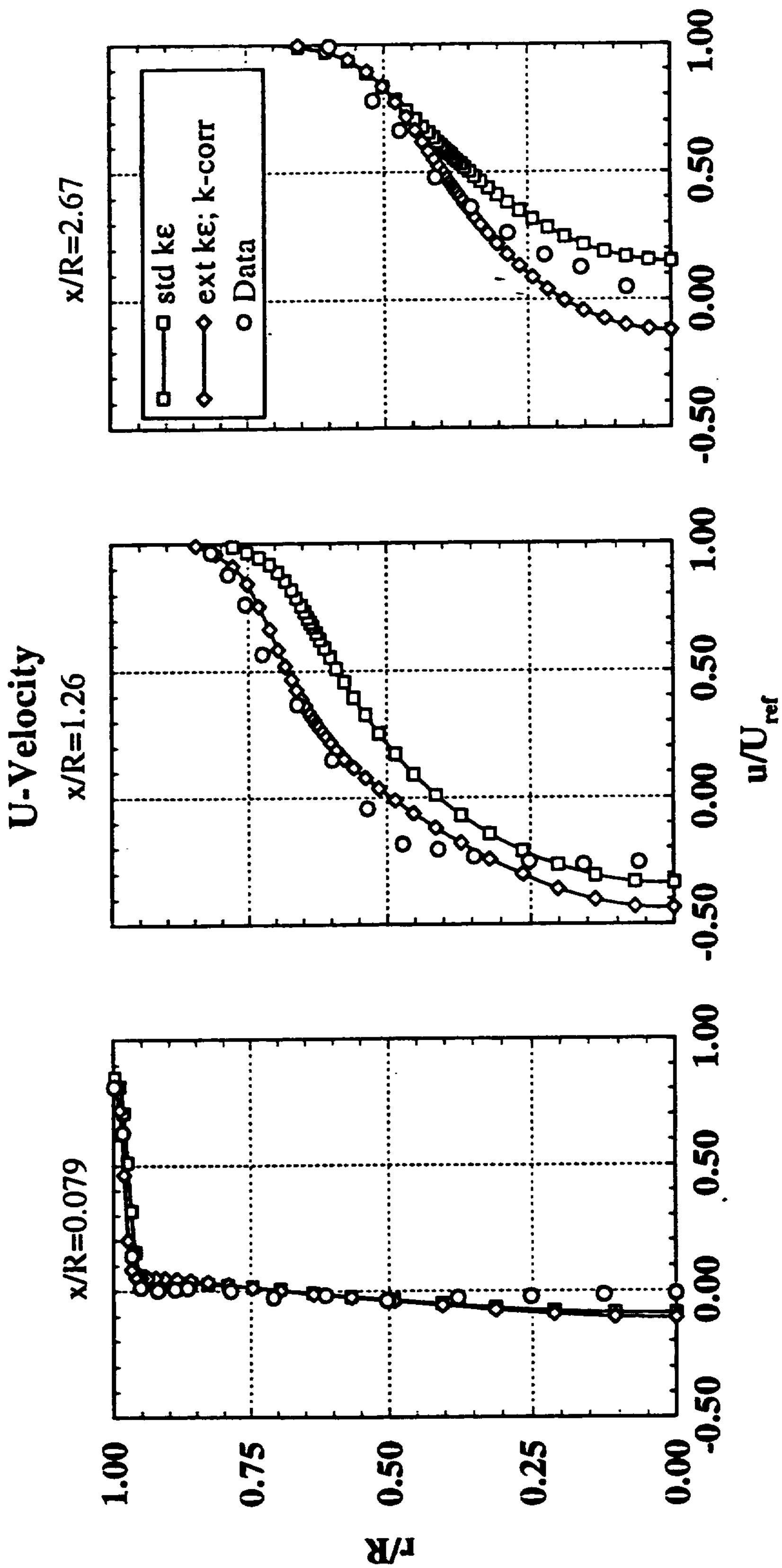
CONTOUR LEVELS
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20
2.30
2.40
2.50
2.60
2.70
2.80
2.90

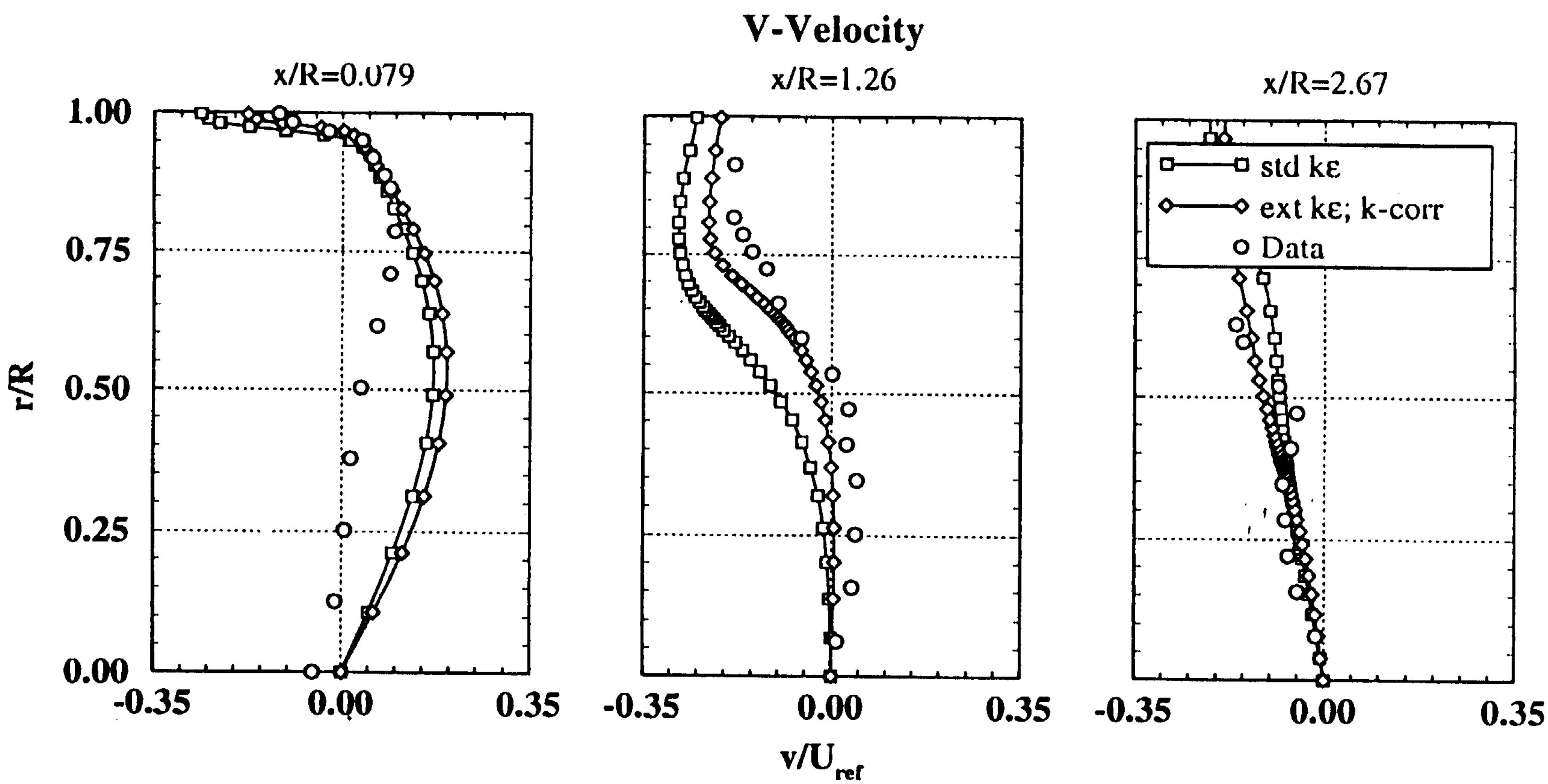
2.460	MACH
0.00 DEG	ALPHA
1.63x10**6	Re
277x101	GRID

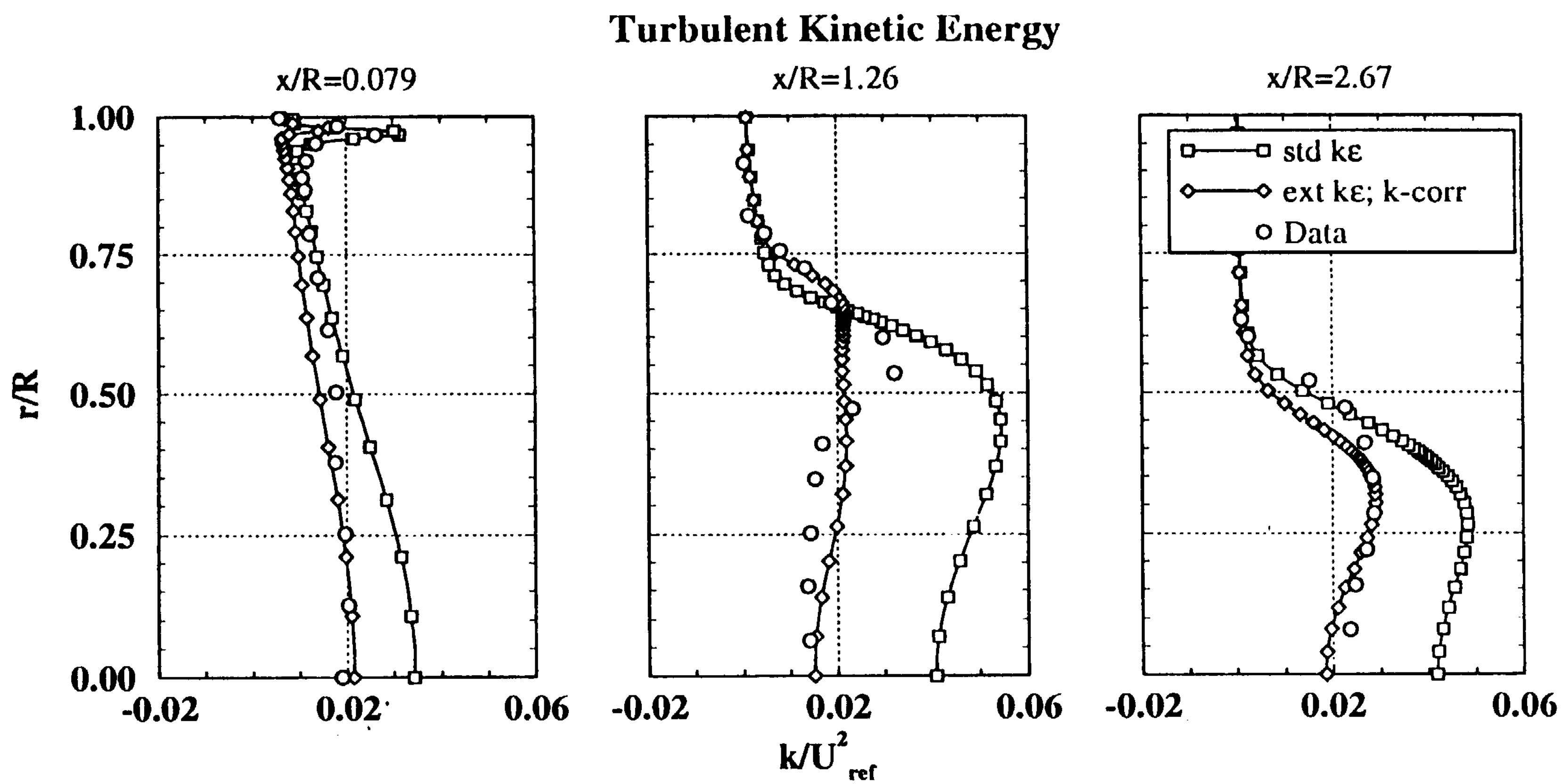


q17.5.img

ORIGINAL PAGE IS
OF POOR QUALITY

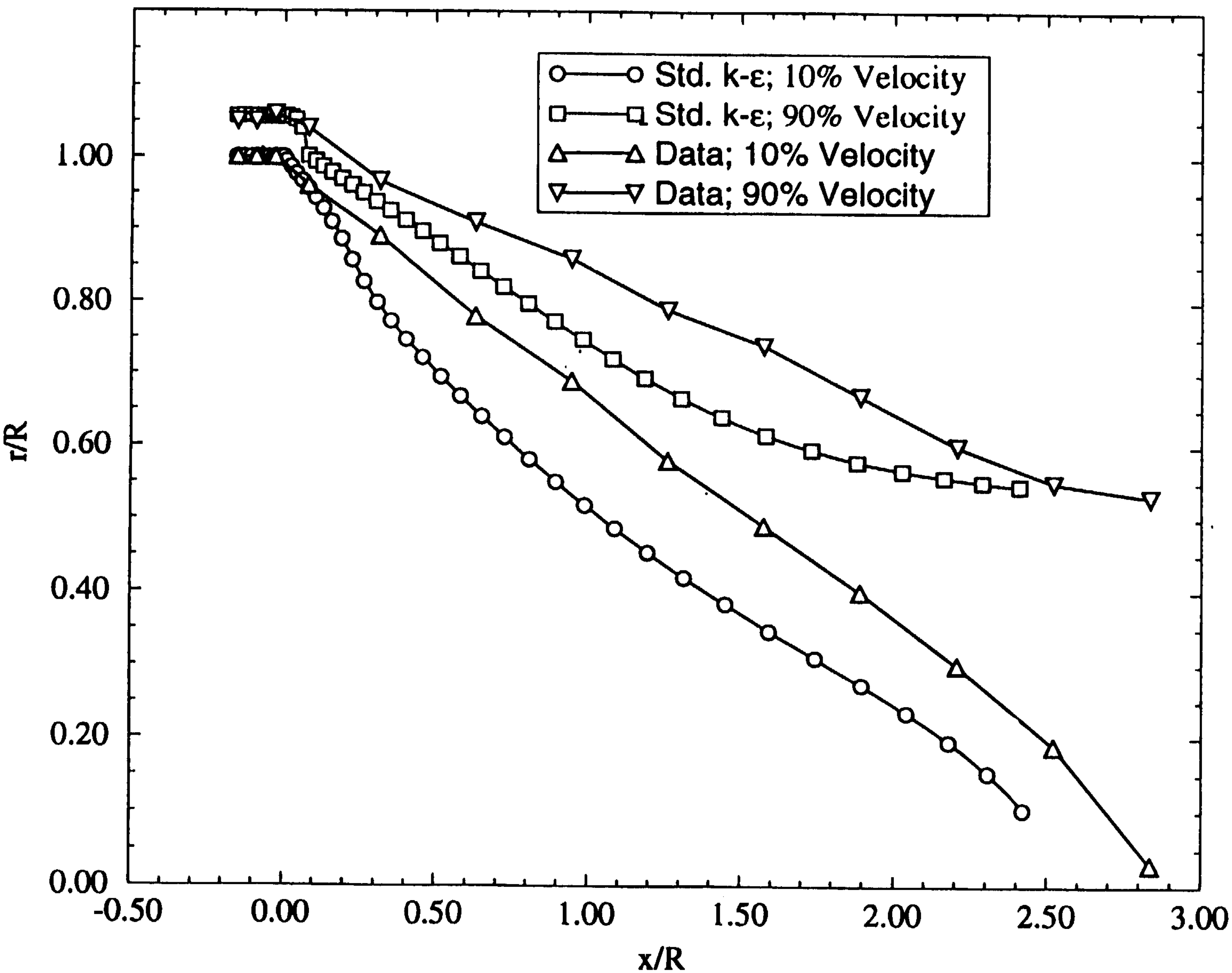

U-Velocity
x/R=0.079
x/R=1.26
x/R=2.67
std kε
ext kε; k-corr
Data
r/R
u/U_{ref}
1.00
0.75
0.50
0.25
0.00
-0.50
0.00
0.50
1.00


V-Velocity
x/R=0.079
x/R=1.26
x/R=2.67
r/R
1.00
0.75
0.50
0.25
0.00
-0.35
0.00
0.35
v/U_ref
std kε
ext kε; k-corr
Data


Turbulent Kinetic Energy
x/R=0.079
x/R=1.26
x/R=2.67
r/R
1.00
0.75
0.50
0.25
0.00
-0.02
0.02
0.06
k/U^2_{ref}
std kε
ext kε; k-corr
Data

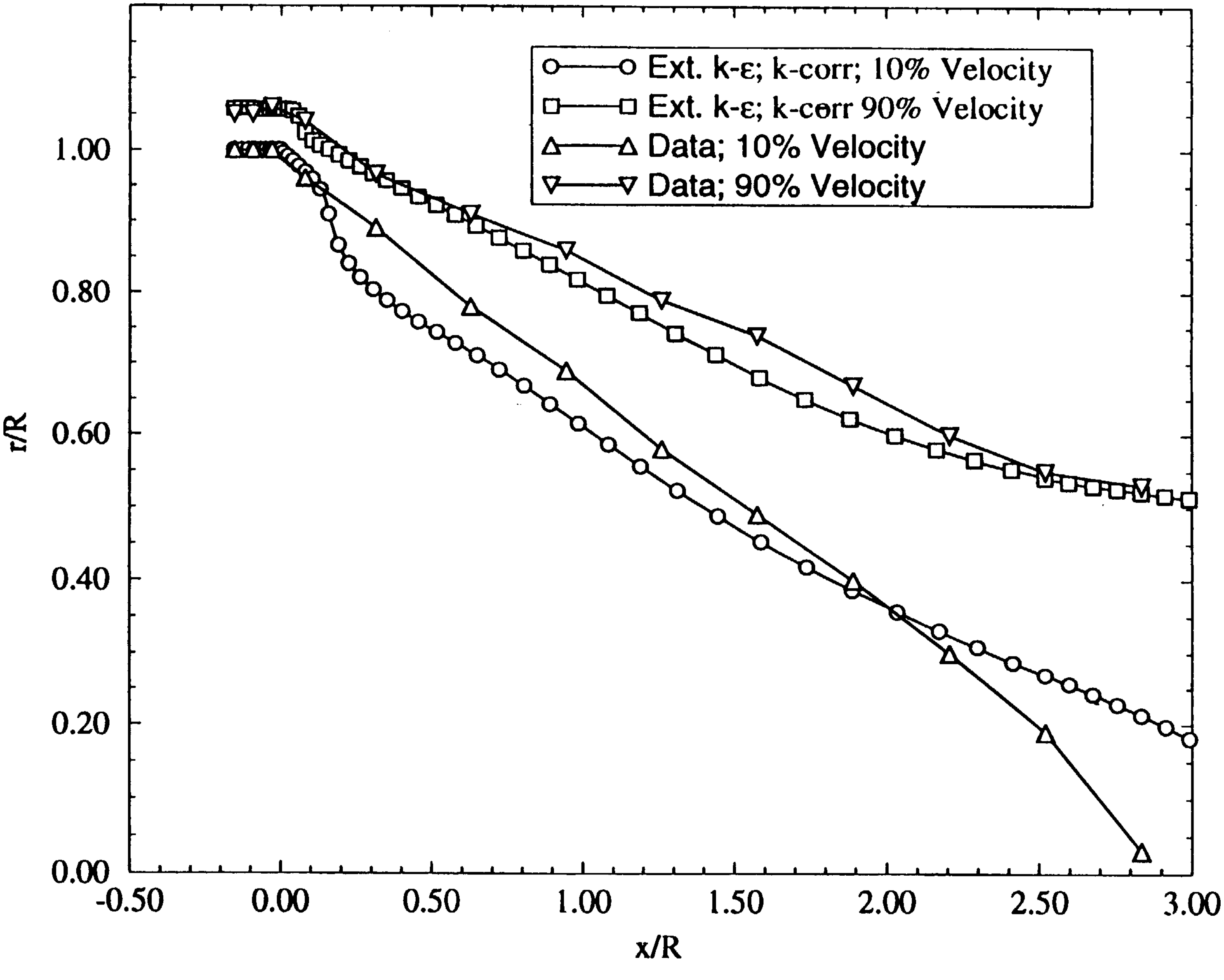
SHEAR LAYER GROWTH

Standard kε Model

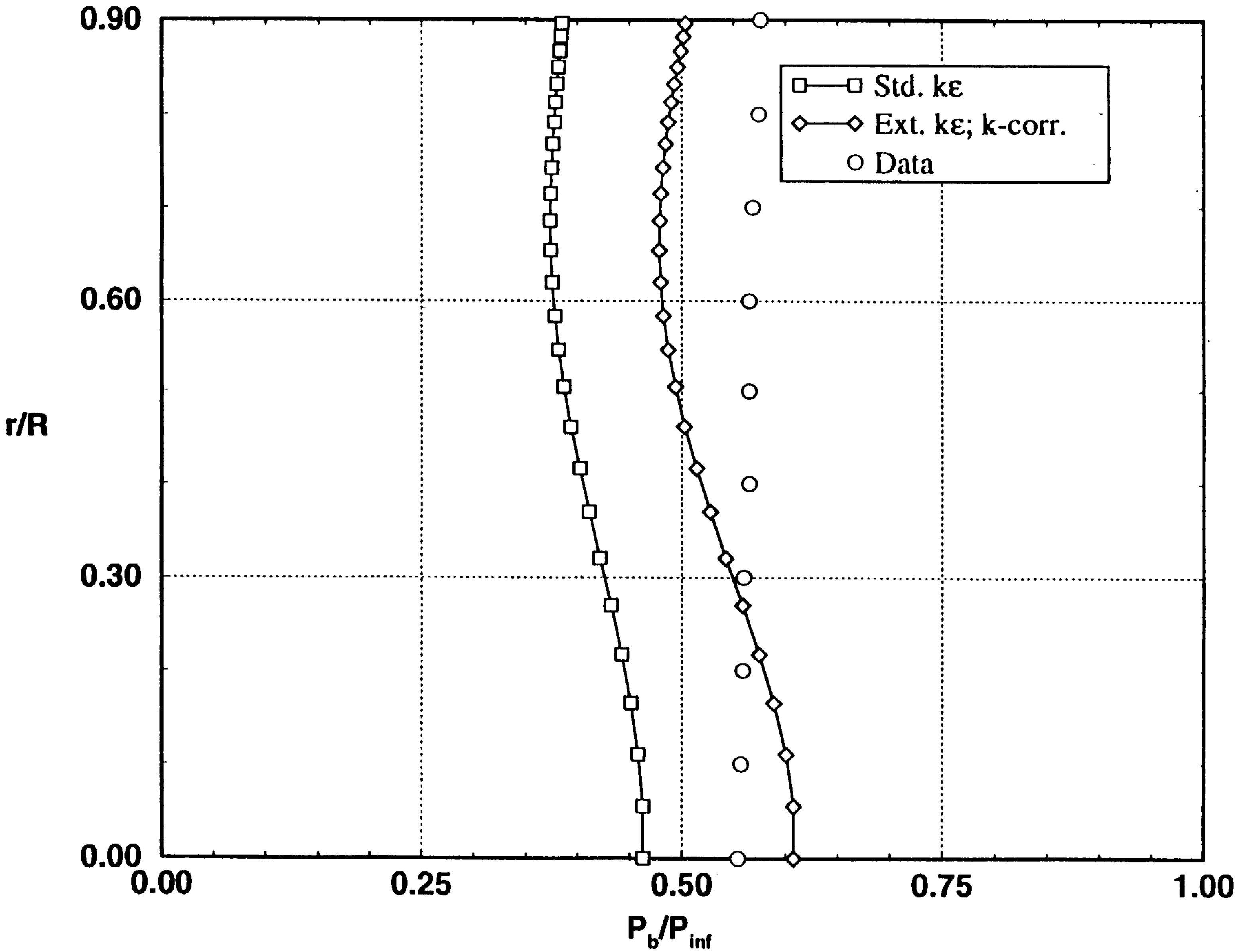


SHEAR LAYER GROWTH

Extended kε Model; k-Correction



Base Pressure



CONCLUSION

• Summary

-Predicted flowfield structure is qualitatively good for all cases

- Vorticity generation in shear layer makes problem more complex
- Standard k-e model over-predicts eddy viscosity resulting in:
  - Very low base pressure predictions
  - Under-predicted reattachment length
  - Over-predicted shear layer growth rate
- Extended k-e model with compressibility correction reduces eddy viscosity resulting in:
  - Much better (but still low) base pressures
  - Over-predicted reattachment length
  - Slightly underpredicted shear layer growth rate
- Overall, extended k-ė model with compressibility correction gives better results

• Future Work

- Dilieate interaction between compressibility and turbulence generation/transport
- Address vorticity generation issue in highly compressible flowfield
- Complete coarse grid cases for guidance on 3-D problems