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

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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

- $M = 2.46$
- $U = 1860.2 \text{ ft/sec}$
- $P_0 = 74.7 \text{ psia}$
- $T_0 = 532.8 \text{ R}$
- $Re = 1.6 \times 10^7 / \text{ft}$

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 TURBULENT KINETIC ENERGY PROFILE

Interpolation

Data

\( \frac{K}{U^2} \) vs. \( \frac{y}{y'} \)

0.010

0.005

0.000

-0.005

-0.010

1.15

1.10

1.05

1.00

-
### SUMMARY of CASES/RESULTS

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TURBULENCE MODELS

• Standard k-ε model

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

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

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

\[
C_1 = 1.43 \quad C_2 = 1.92 \quad S_{c_k} = 1.0 \quad S_{c_\varepsilon} = 1.92
\]
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 \( \varepsilon \) in the k-eqn source term

where \( M_t^2 = \frac{k}{a^2} \)
SHEAR LAYER GROWTH

Standard $k\varepsilon$ Model

- ○ Std. $k\varepsilon$; 10% Velocity
- □ Std. $k\varepsilon$; 90% Velocity
- △ Data; 10% Velocity
- ▽ Data; 90% Velocity

Graph showing the growth of a shear layer with different velocities and data points.
SHEAR LAYER GROWTH

Extended $k\varepsilon$ Model; k-Correction

- Ext. $k\varepsilon$; k-corr; 10% Velocity
- Ext. $k\varepsilon$; k-corr 90% Velocity
- Data; 10% Velocity
- Data; 90% Velocity
CONCLUSION

• Summary

- Predicted flowfield structure is qualitatively good for all cases
- Vorticity generation in shear layer makes problem more complex
- Standard k-ε model over-predicts eddy viscosity resulting in:
  - Very low base pressure predictions
  - Under-predicted reattachment length
  - Over-predicted shear layer growth rate
- Extended k-ε 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-ε model with compressibility correction gives better results

• Future Work

- Dilute 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