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AFTERBODY EXTERNAL AERODYNAMIC AND PERFORMANCE PREDICTION AT HIGH REYNOLDS NUMBERS

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Afterbody External Aerodynamic and Performance Prediction at High Reynolds Numbers

- Overview
- CFD Method
- Grid Convergence
- Reynolds Number Trends
- Concluding Remarks

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slide 2

Historically there has been more experience with sub-scale testing and flow analysis. The last few decades have been addressing the issue of flight versus sub-scale flow more completely than before. In 1974, as part of the NTF run-up work, a set of simple test bodies were run in the 0.3-m Cryogenic Pilot Tunnel, obtaining a set of pressure data over a large Reynolds number range.

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PAB3D is a Reynolds averaged Navier-Stokes method that has been extensively utulized for analysis of aerodynamic and propulsion-aerodynamic interactions involving shear flows, jet-plumes, and massively separated boundary layer flows. The last year of work has been used analyzing the capability of the anisotropic algebraic Reynolds stress turbulence models some results of which are to follow. The Girimaji ARSM is fairly recent work with PAB3D being the first RANS code to implement this work. Dr. Girimaji worked for both Shih and Lumley.

OVERVIEW

- Considerable model-scale experience and data base.
  - Wind tunnel data
  - Most CFD done on wind tunnel models
- Model-scale vs. Full-scale flow characteristics
  - Boundary layer growth modified
  - Subsequent changes in shocks and shock-b.l. interactions
  - Changes in drag and lift increments
- Cryogenic test performed on an axisymmetric afterbody (Reubush, 1974)
  - C_p , $C_{d,\beta}$ data obtained
  - Reynolds number range from 10 to 120 million

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PAB3DV13R

- 3-D RANS Upwind Method
- Multiblock with general face patching and mesh sequencing
- Mixed Roe and van Leer solver schemes
- Third order solver accuracy with local time stepping
- Linear 2-equation k-ε turbulence model
- Algebraic Reynolds Stress turbulence models
  - Shih, Zhu, & Lumley
  - Girimaji
- Real gas and multi-species
- 23 words per grid point
- 38 μsec per iteration per grid point (Cray YMP)

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NASA TND 8210 is a report by D.Reubush from 1974 when he performed a series of tests to determine Reynolds numbers effect for nozzle-boattail flows. Several models and nozzle configurations were tested in both the 0.3m Cyrogenic Pilot Tunnel and the 16-Foot Transonic Tunnel.

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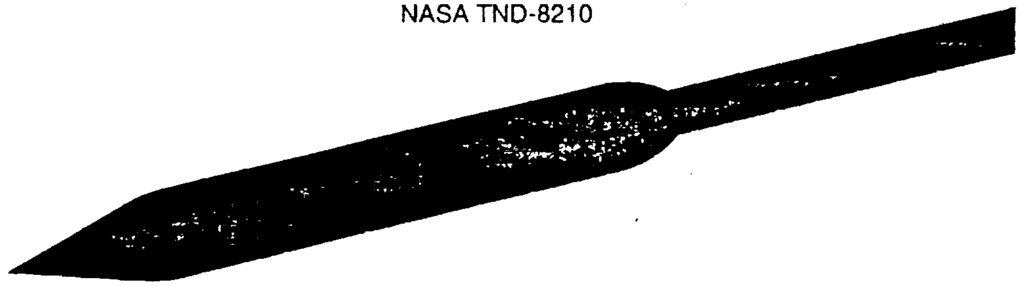
Computations performed over a small Reynolds number range could tolerate using the same grid for each set of conditions. The range of these calculations though required a miminum of 3 grids to keep the nondimensional boundary layer parameter y+ between 0.2 and 0.5. The assumption of a zero pressure flat plate flow using free stream conditions provide a fairly accurate first guess for boundary layer griding parameters.

AXISYMMETRIC AFTERBODY W/ SOLID STING
NASA TND-8210



Modeled after Configuration 1, NASA TND-7795
Two cryogenic model lengths for this nozzle
- L = 8 inches (1/6 th scale of Conf.1)
- L =16 inches

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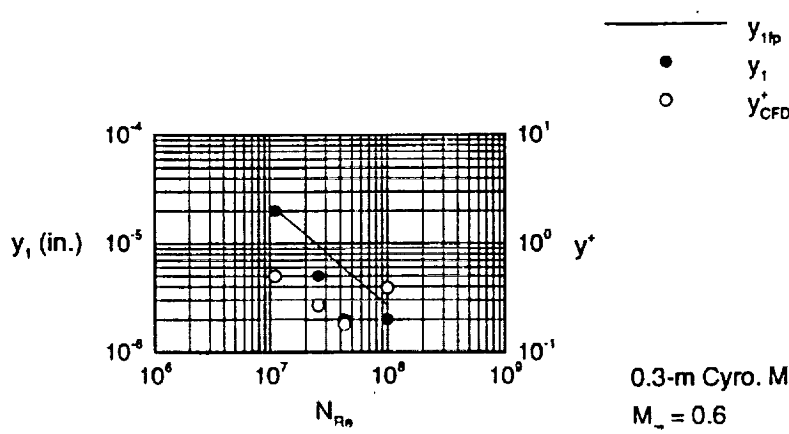

0.3-m Cyro. Model
$M_\infty = 0.6$

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Both algebraic Reynolds stress models Shih, Zhu and Lumley; and Gatski and Speziale had very consistent trends over the local Reynolds number range from less that 0.1 to 200. million following fairly closely the flat plate parameter of average skin friction. Prandtl-Schlichting is the predicted high Reynolds number trend of average skin friction.

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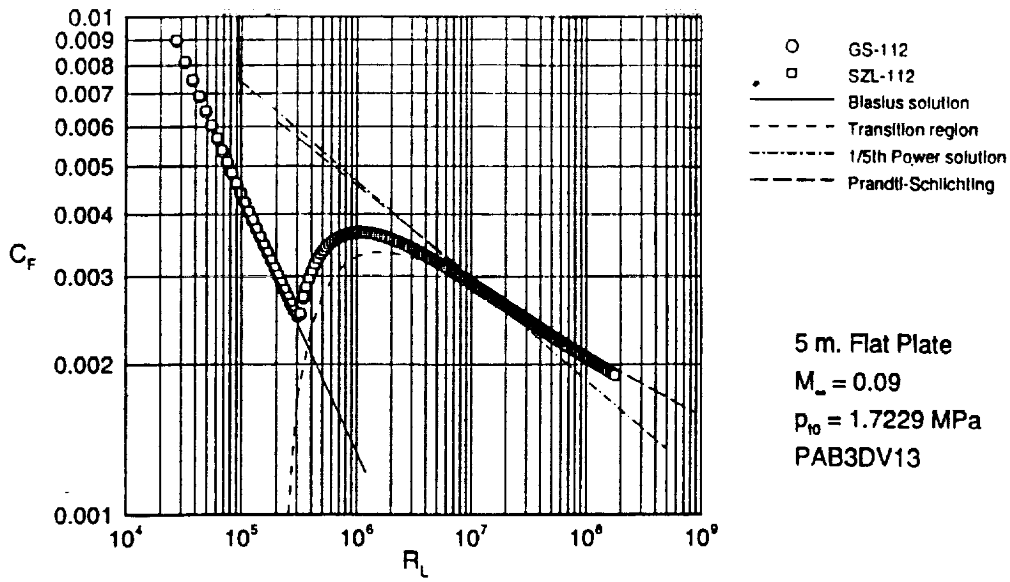
Fairly good grid convergence was achieved, shown by this representative plot at 43 million Reynolds number. The boundary layer at M=0.6 does separate downstream of 0.65, but this separation is due to purely the adverse pressure gradient of the boattail flow. The boundary layer separation that occurs at M=0.9 is a shock induced separation. Duplicate experimental data points are shown for an indication of data scatter.

AVERAGE SKIN FRICTION - SUBSONIC FLAT PLATE



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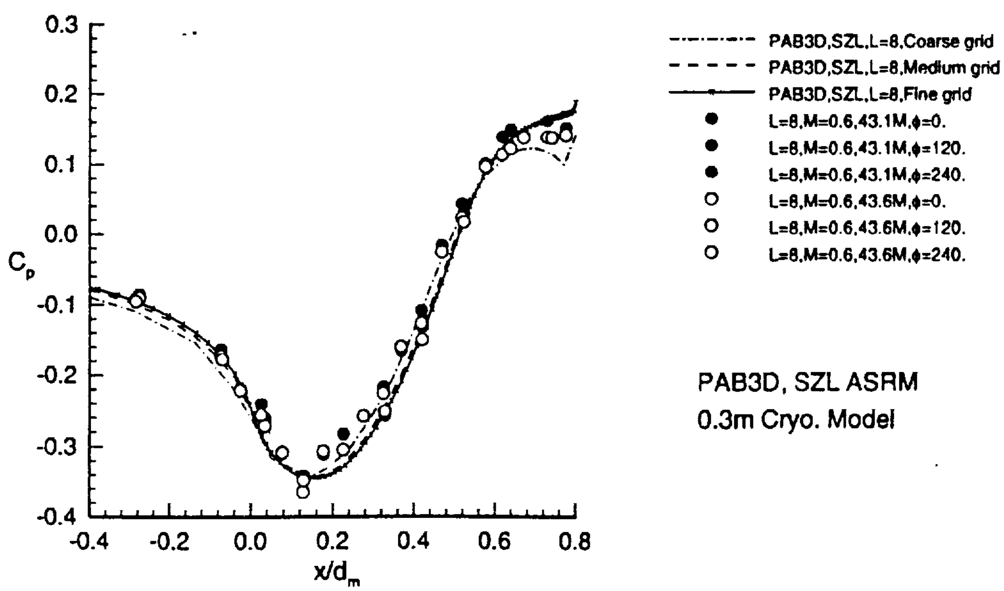
AXISYMMETRIC AFTERBODY W/ SOLID STING
Grid Convergence



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The CFD pressure distributions on the boattail show a very consistent Reynolds number trend with the shock strength generally increasing with Reynolds number and the pressure recovery increasing as well. The experimental data plotted was a cubic spline fit through several repaat points in an attempt to show a single "clean" distribution at the two Reynolds number settings. The spline was fairly poorly fitted upstream of x/dm = 0. The change in the experimental pressure distributions with Reynolds number was slightly less than that predicted by CFD. The changes observed in the pressure distributions tended to cancel each other out when the integrated drag was obtained.

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Integrated pressure drag for several experimental models and for the CFD are shown. A conclusion drawn in NASA TND 7795 was the extreme sensitivity of pressure drag to very small changes in pressure distributions. The pressure distributions between the same model tested in both the 0.3m tunnel and 16-foot and the CFD are visually very similar, but as seen comparing the open diamond, triangle, and closed square with the open square around 10 million Reynolds number there appears to be about a factor of 2 difference in drag. The X around 12 million is the 48 inch model that the cryogenic models were designed after and whose drag was fairly closely matched by the CFD. Overall, there appears to be only a very mild variation in drag with Reynolds number at this Mach number.

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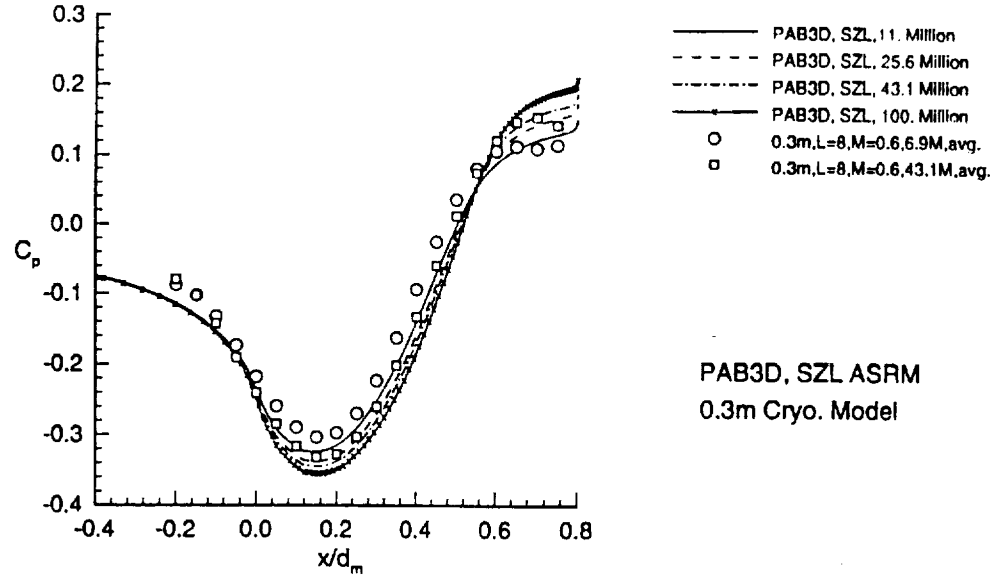
AXISYMMETRIC AFTERBODY W/ SOLID STING

Reynolds Number Variation of Boattail C_p



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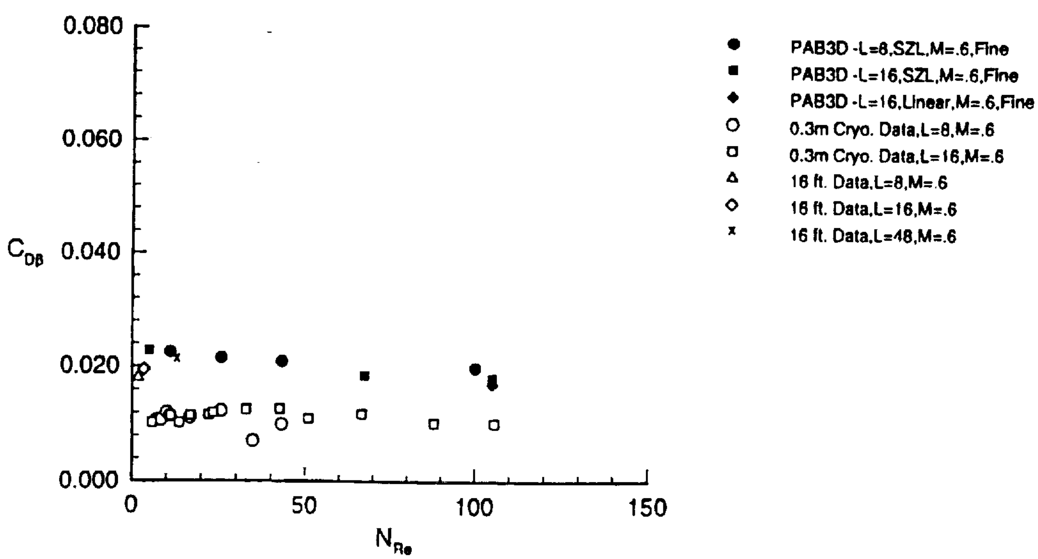
Reynolds Number Trend of Integrated Boattail Pressure Drag



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slide 10
A larger scatter in the integrated drag data occurs at M=0.9 resulting in no quantitative conclusion in the variation pressure drag with Reynolds number for the particular geometry, except that potentially it is fairly small.

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The wetted area equivalent flat plate skin friction numbers are compared to the skin friction calculated by the code. In general the change in skin friction is slightly lower using the CFD. The CFD was 5 counts below the 1-D theory at 10 million Reynolds number and about 2 counts below at around 100 million Reynolds number. These are drag coefficients based on the maximum body cross-sectional area.

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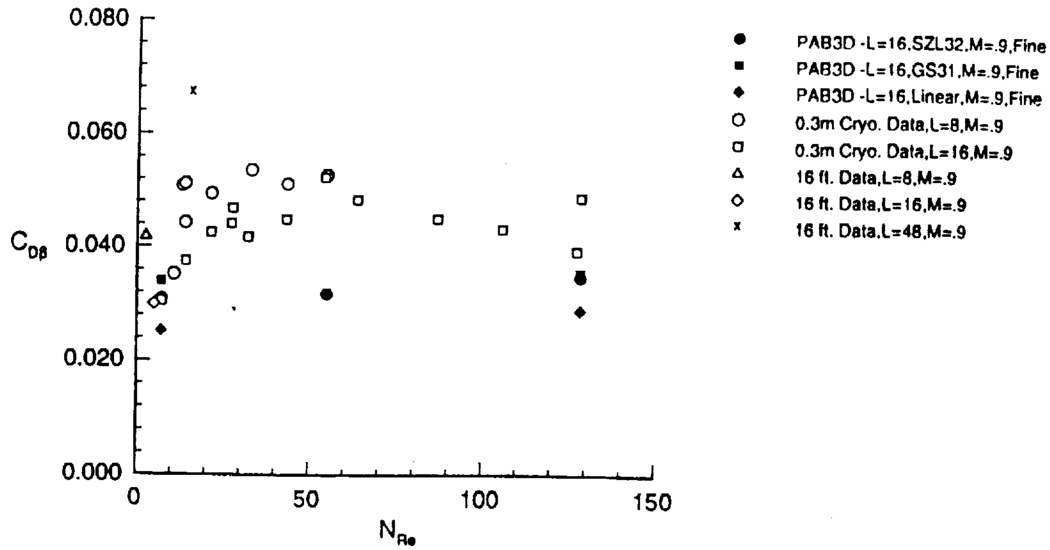
Reynolds Number Trend of Integrated Boattail Pressure Drag



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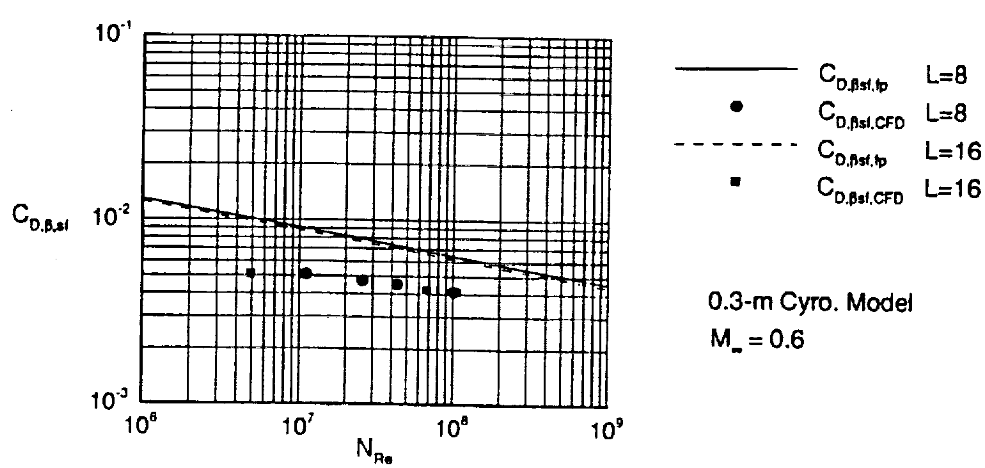
Nozzle Boattail Skin Friction With Reynolds Number



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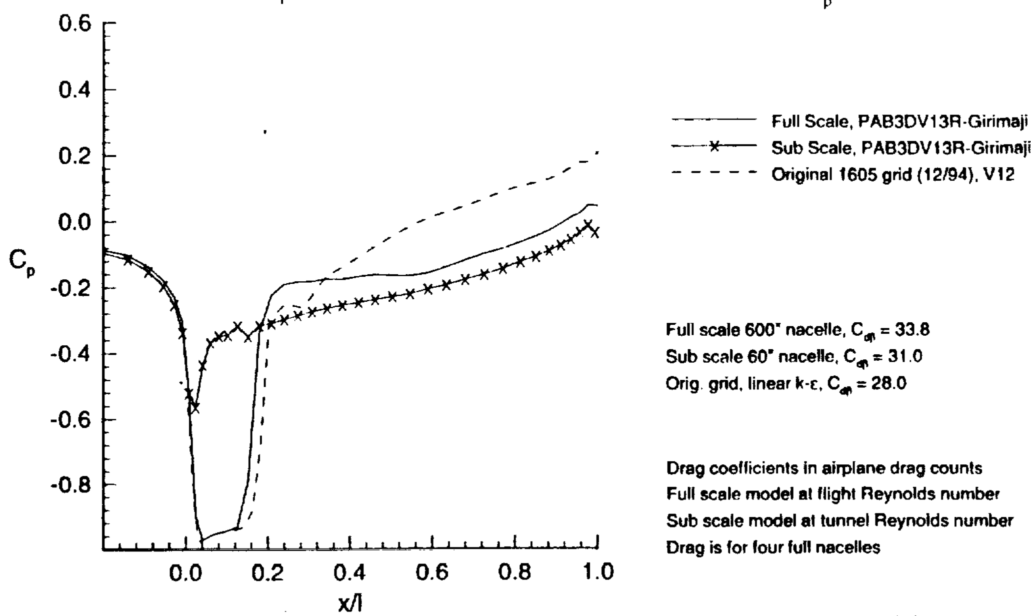
slide 12

This CFD experiment concludes that the potential difference between the flow between a flight Reynolds number test and a sub-scale wind tunnel test are substantial for this particular nozzle boattail geometry. The early study was performed using a linear k-epsilon turbulence model. The present study was performed using the Girimaji formulation of a algebraic Reynolds stress turbulent simulation. The dashed line is the pressure distribution from the original isolated transonic boattial study leading up to the previous presentation by Midea, Pao, Austin and Mani; performed by Pao, Abdol-Hamid and Carlson. The solid line is the same flight scale geometry with some regridding performed for better grid convergence. The solid line with x is the same geometry scaled down to the size of a typical jet effects model that could be tested in the Langley 16-Foot Transonic Tunnel at a lower Reynolds number. In general, the shock is considerably weaker with a more extensive flow separation at the lower Reynolds number. It is likely due to the different boundary layer growth characteristics at the two Reynolds numbers.

CONFIGURATION 1605 - M = 0.95
Comparison of Model-scale With Full-scale Boattail C_p's



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- Skin friction characteristics with Reynolds number consistent
- Grid converged solutions obtained over Reynolds number range.
- Fairly accurate prediction of shock and separated flow pressure recovery.
- Reynolds number trend of surface static pressure coefficients qualitatively achieved.
- CFD slightly over-predicted change in pressure coefficients with Reynolds number.
- Integrated pressure drag on nozzle boattail generally off potentially due to tunnel effects.
- Conducted CFD experiment on configuration 1605. (PAB3DV13R, Girimaji ASM)
  - Full-scale model solution had a large separation and low recovery pressure.
  - Sub-scale model solution had a weaker shock and yet larger separation predicted.

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