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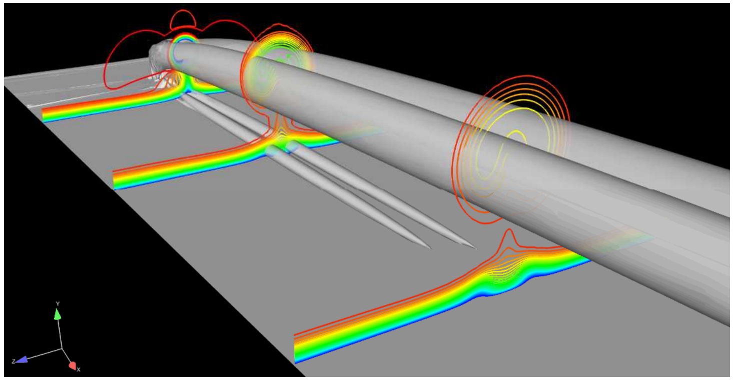

Evaluation of Two-Equation RANS Models for Simulation of Jet-in-Crossflow Problems

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Outline

- Background and Motivation
- Objectives
- Approach
  - Flow Configuration
  - Code and Numerical Methods
  - Turbulence Models
- Results
- Analysis
- Conclusions & Future Work

Background And Motivation

- Jets-in-Crossflow have Wide Range of Applications
  - Fuel injection in combustors
  - Thrust vectoring and roll control jets Etc.
- Jet-fin Interactions In Roll Control Jets
  - Overall moments generated can be less than moments due to jet thrust alone
  - Induced velocity due to vortices generated by jets modify the effective angle of attack on fins and hence forces and moments generated by fins – "Counter Torque"
  - Induced Velocities are a function of distance from vortex core and vortex strength

Accurate Predictions of Vortex Locations and Strength are Needed

Background And Motivation

- Recent Approaches for Modeling Jets-in-Crossflow
  - Move towards LES of these flowfields
  - LES is still too expensive in the design environment

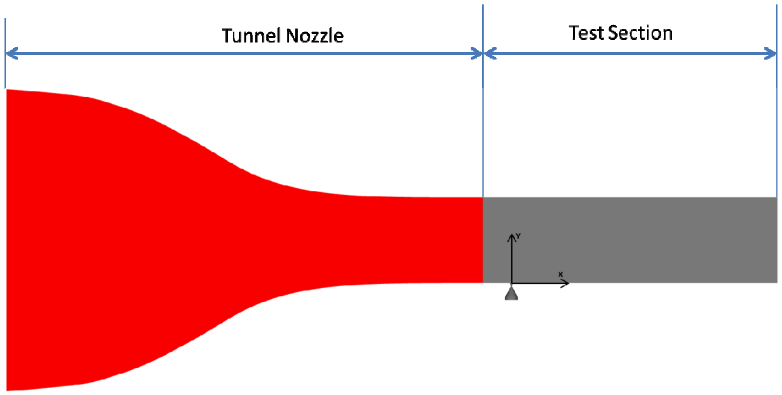
- RANS modeling:
  - Has been found to be deficient for vortical flows in general
  - Modifications, Corrections and Sensitization Procedures have been proposed for such flows
  - No analysis to the best of our knowledge on the effects of these on vortex location and strength predictions
  - Or Jet-fin interaction predictions

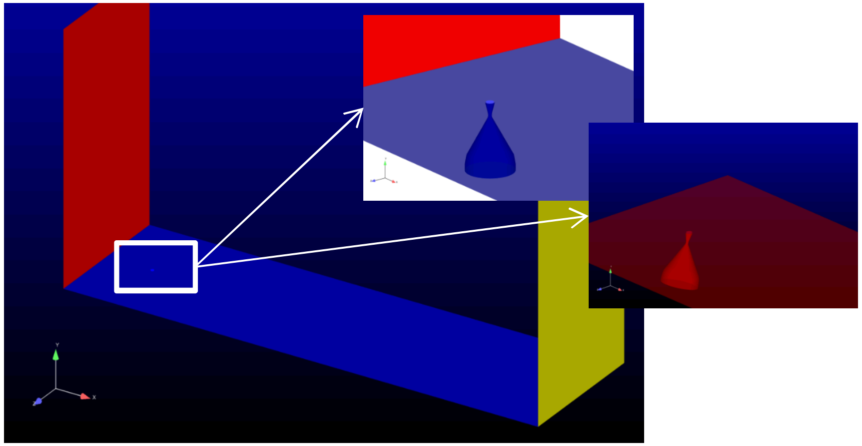
Objectives

- Evaluate the performance of two-equation RANS models for the prediction of Jets-in-Crossflow
  - Of primary interest is the Supersonic Jet in Subsonic crossflow experiment of Beresh et al.
    - AIAA J V 43 No. 2, 2005
    - AIAA J V 43 No 11 2005
    - AIAA J V 44 No. 12 2006
  - Focus is on evaluating the ability to accurately predict vortex strengths and locations
    - Detailed experimental data characterizing these quantities available
    - Of Interest: Vertical AND Canted Jets

Flow Configuration

- Simulate Experiments Conducted in the Sandia TWT Facility
  - 12” Square Test Section
  - Long Nozzle Block Upstream of the test section
    - Large Boundary Layer relative to jet diameter
  - Jet issues from 0.375” exit diameter nozzle mounted on the floor (ceiling) of TWT test section





Flow Conditions

- Data Available at Wide Range of Conditions

	0.5	0.6	0.7	0.8
16.7				☑
10.2	☑	☑	☑	☑
5.6				☑
2.8				☑

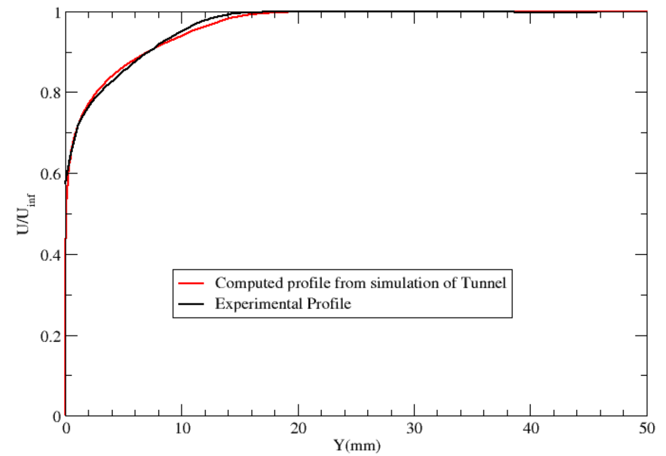
  - Current Study Focuses on Higher Mach and J Regime
- Data Also Available for Canted Nozzles
  - Cant Angles 0°, 15°, 30°, 45°
  - Current work uses only 15° data

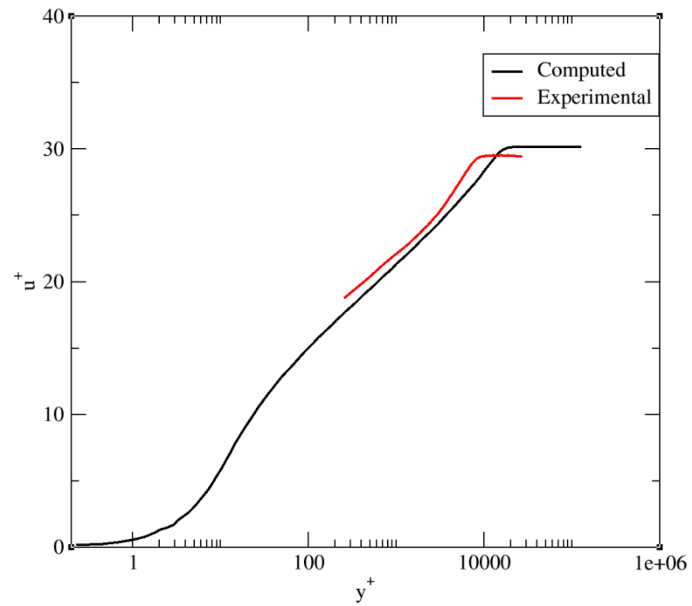
Code and Numerical Methods

- GASP Commercial Software From Aerosoft Inc.
  - Solves the RANS equations
    - Wide range of Turbulence Models available including algebraic, one-equation, two-equation models and DES, SST-DES.
    - Turbulence equations are solved fully coupled with primary conservation equations
  - Steady State Solution Obtained by Time Marching
    - Explicit RK schemes
    - Implicit Using Gauss-Seidel/Block Jacobi Solver
  - Supports Unstructured and Chimera meshes
    - Only Block Structured point matched meshes used here.
  - Several Flux Functions available
    - Roe Scheme used here.
  - Parallelization using MPI

Simulation Procedure

- Boundary Conditions
  - A full simulation of the TWT wind tunnel at the Mach # condition was run to compute the inflow boundary layer for the jet in cross flow simulation.
  - The profile at the location corresponding to the inflow station of the jet in cross flow domain was extracted and provided to GASP as inflow boundary condition
  - The Tunnel walls (side and top) were modeled as slip walls to minimize the number of mesh points in the tunnel boundary layers on the opposite and side walls.

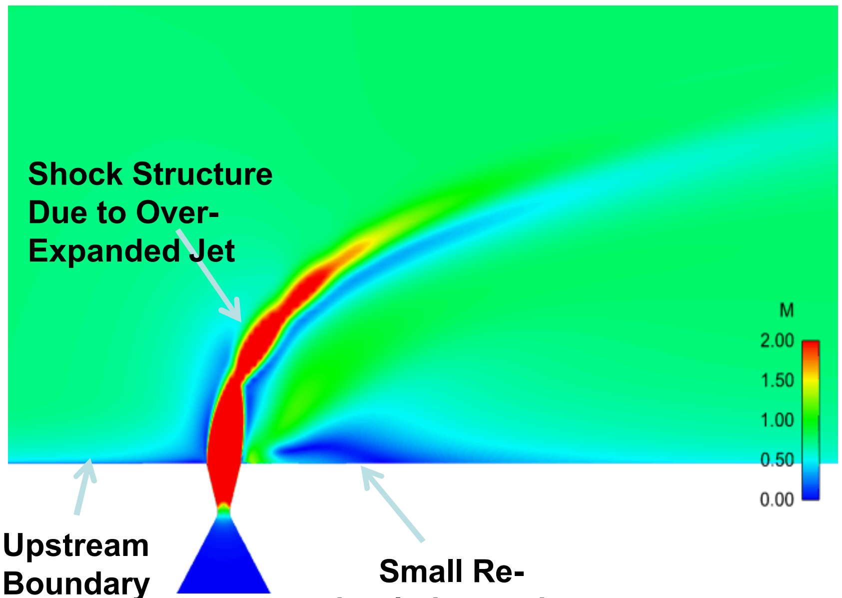


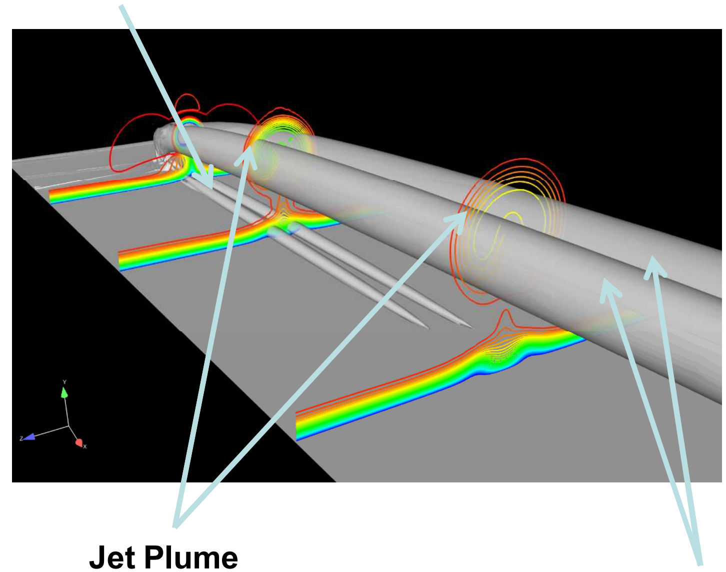


Turbulence Models

- Only Two-Equation Model Family Studied Here
  - K-ε model with Lam-Bremhorst wall damping
    - No Converged Solutions could be obtained. Dropped from analysis.
  - K-ω models
    - Wilcox 1998, Wilcox 2006, Menster-SST
  - Compressibility Corrections (Wilcox)
    - All cases were run with and without compressibility corrections
  - Convergence determined by monitoring wall pressures on a spanwise line downstream of the jet.

Results: M=0.8 J=10.2: Gross Features

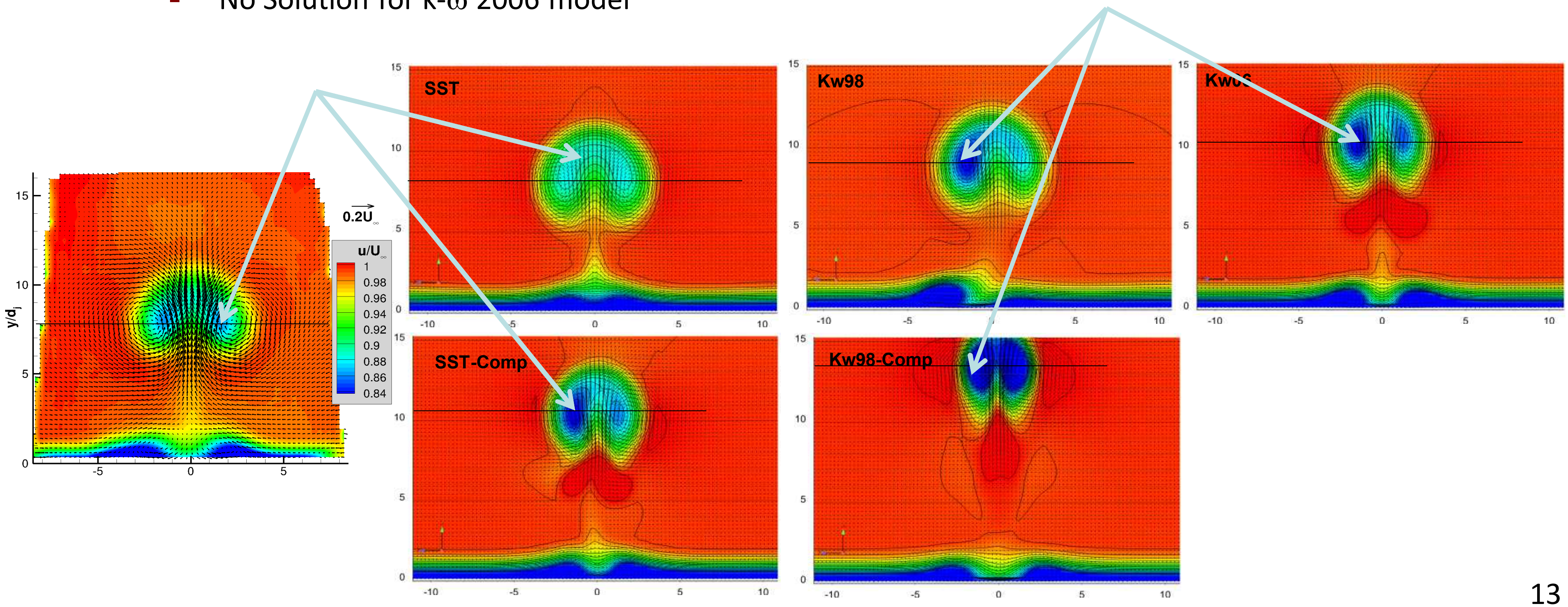




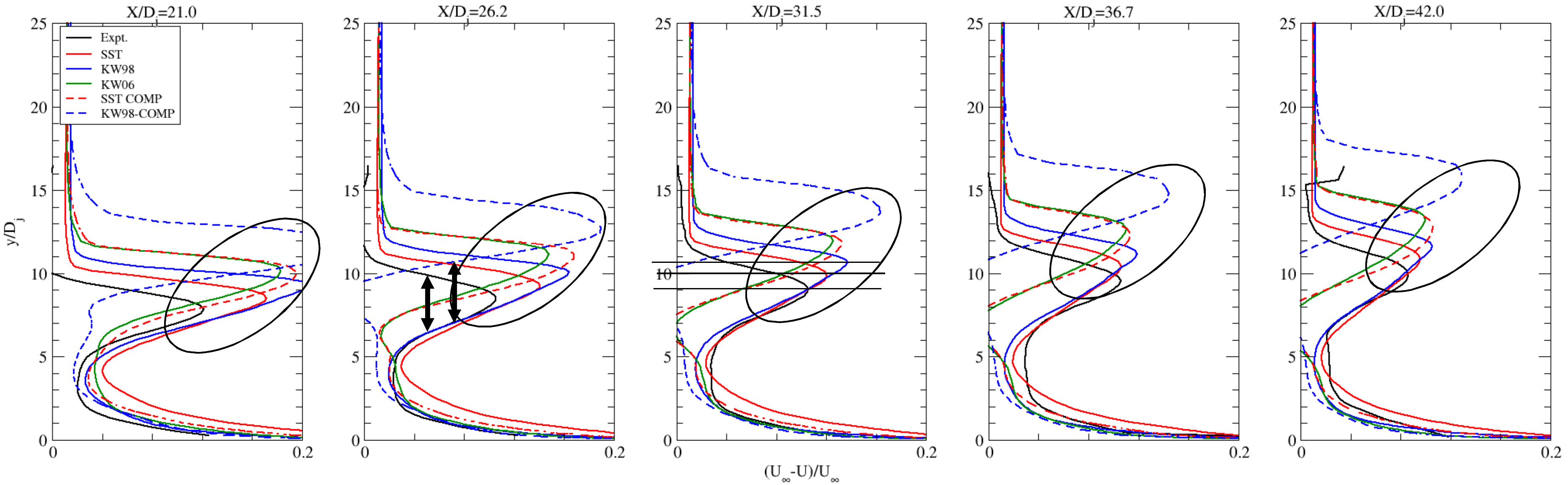
Results: M=0.8 J=10.2: Jet and Vortex Structure

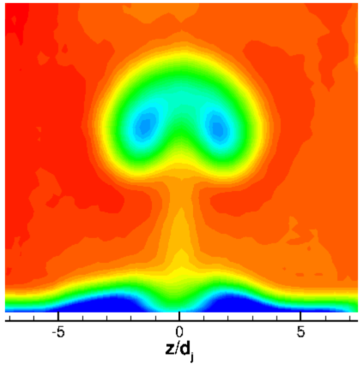
Expt.

- Compared against PIV at x=33.8D_j
- All Models Generally Capture Shape and Gross Behavior
  - Jet Plume with Counter Rotating Vortex Pair Just Under the Plume
  - Horse shoe vortex pair close to the floor
- None of the models capture the velocity deficit or vortex location correctly
  - Models with Compressibility Corrections do worse
  - No Solution for k-ω 2006 model

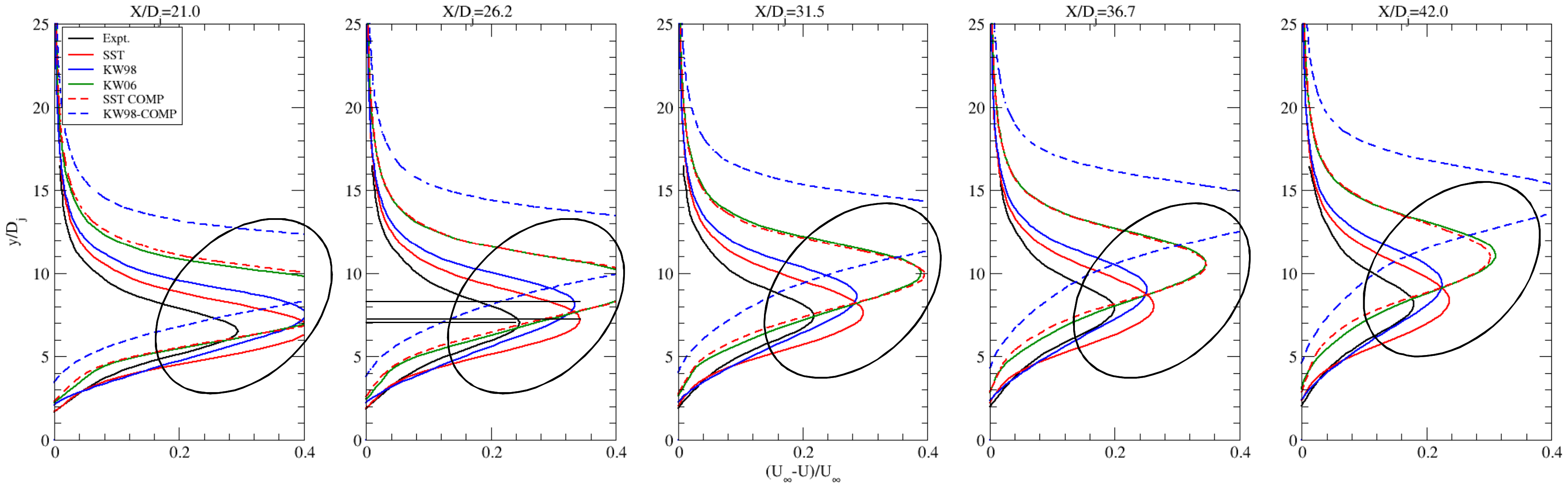


Results: M=0.8 J=10.2: Mean Velocity Deficit

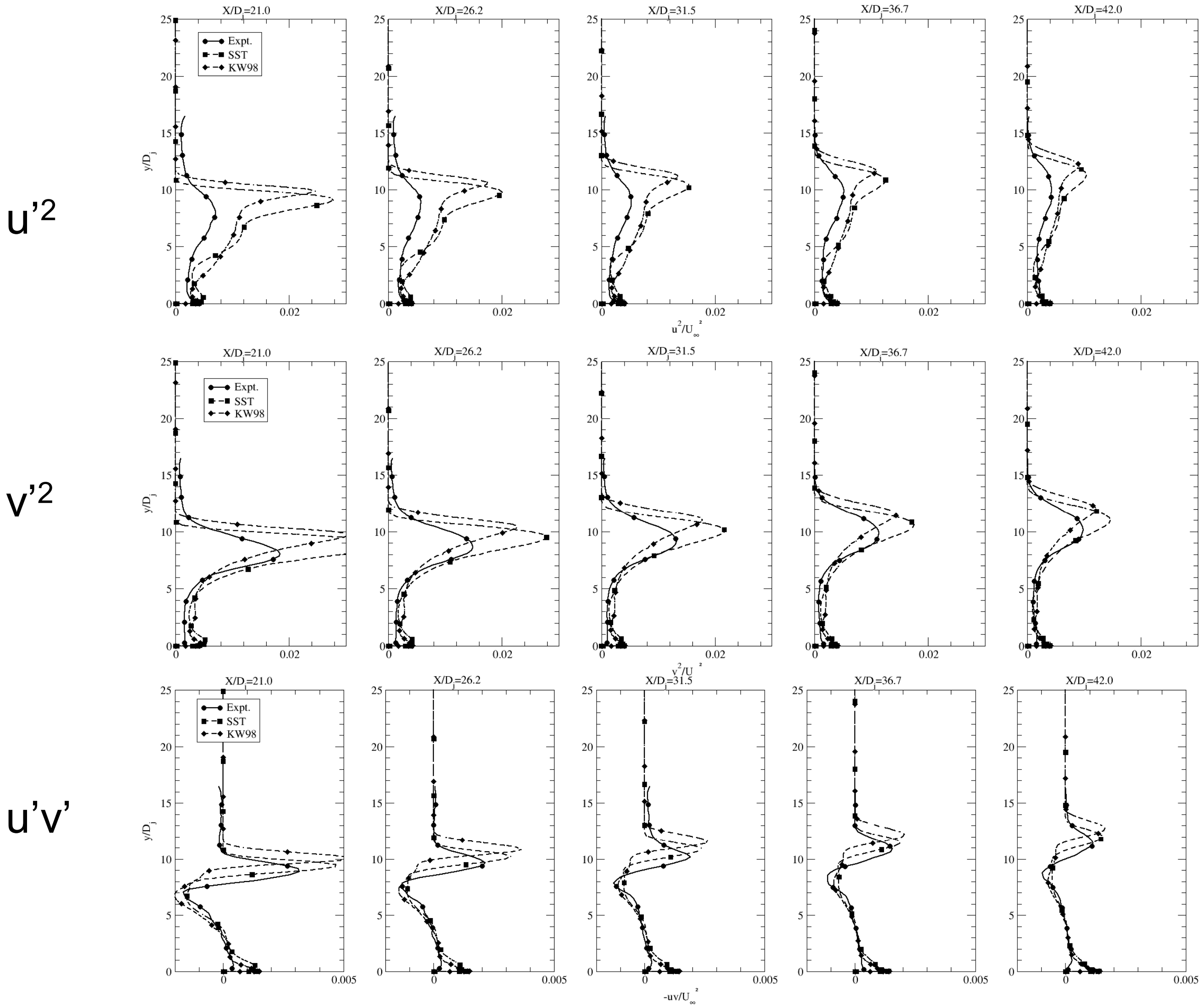




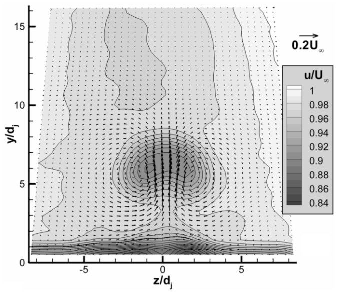
Results: M=0.8 J=10.2: Mean Vertical Velocity

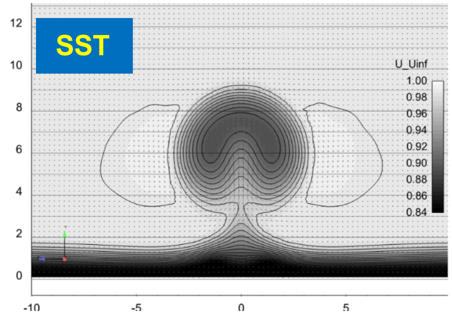


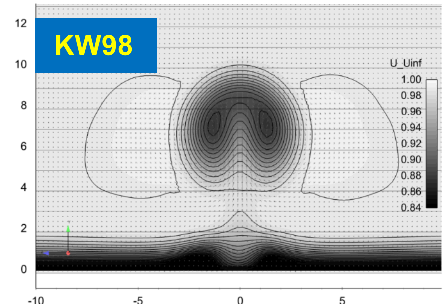
Results: M=0.8 J=10.2: Turbulent Stress Profiles

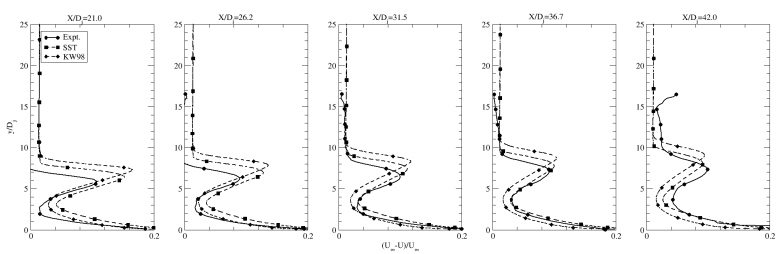


Results: M=0.8 J=5.6

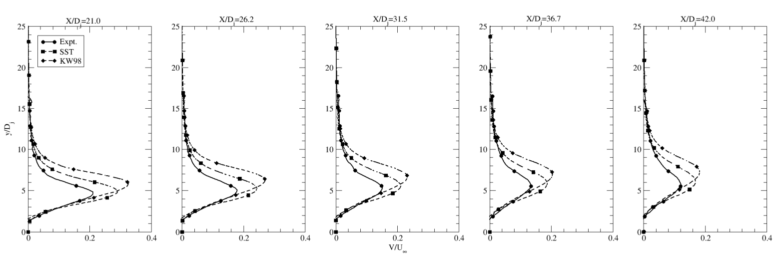




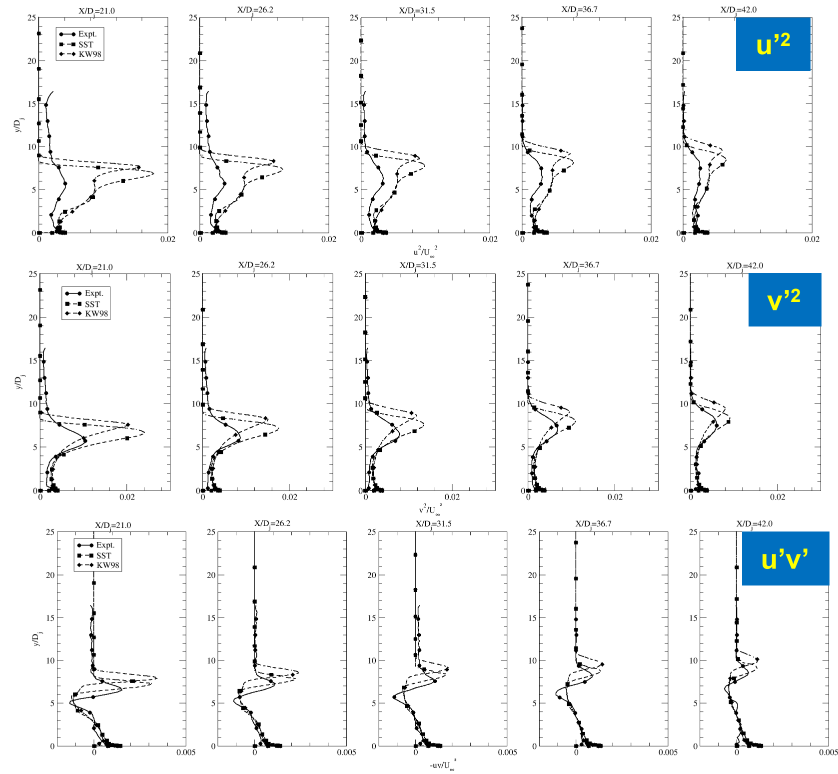




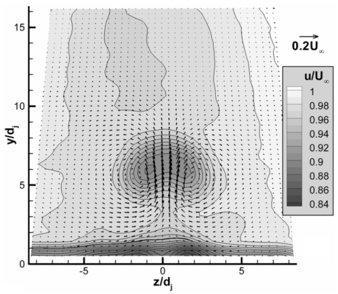
Streamwise Velocity Deficit

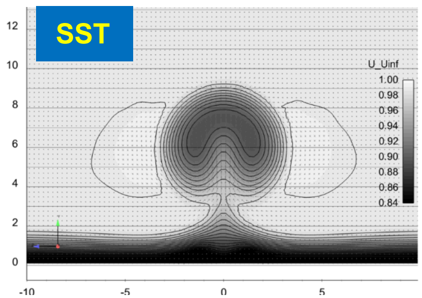


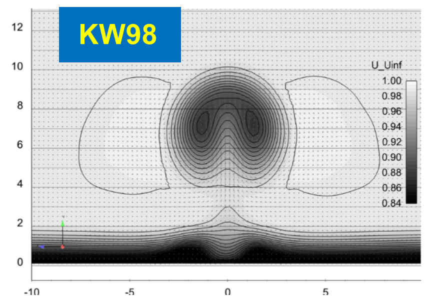
Vertical Velocity

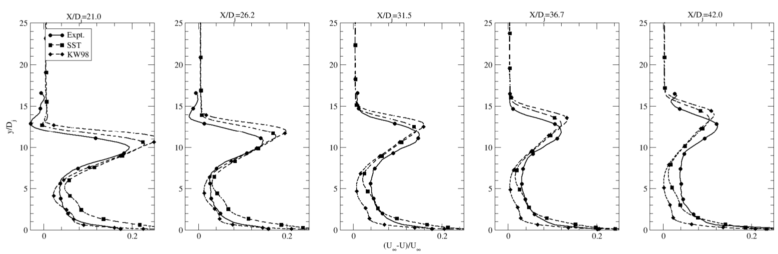


Results: M=0.8 J=16.7

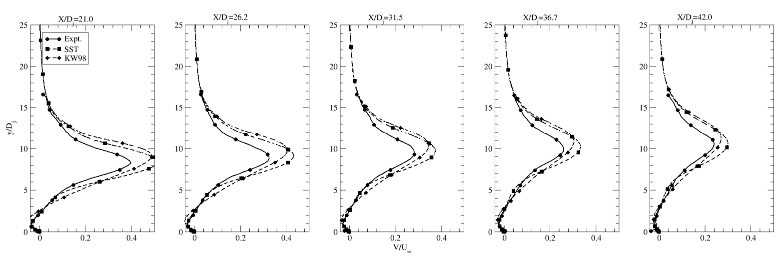




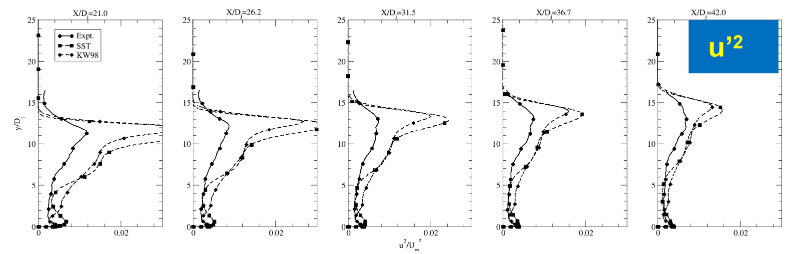


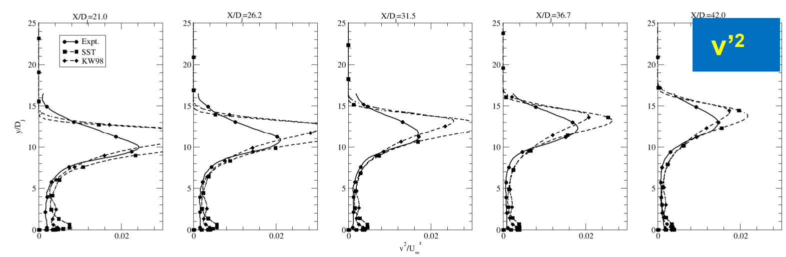


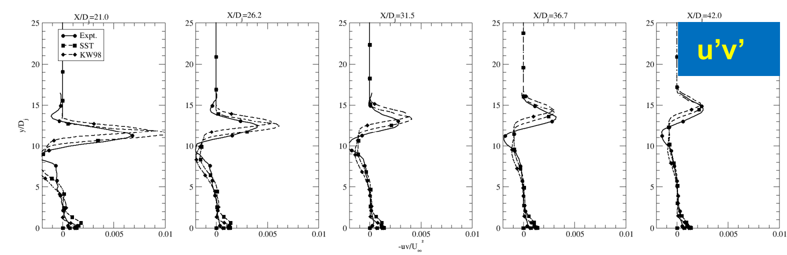
Streamwise Velocity Deficit



Vertical Velocity







Analysis of Experimental Data

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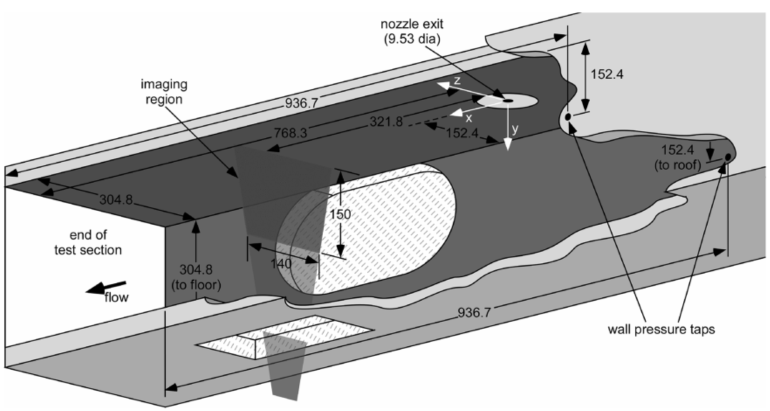
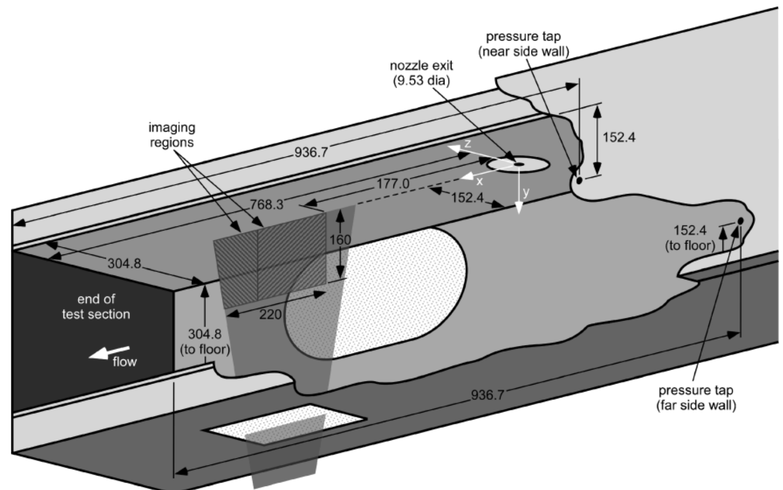
- PIV Data Available on two Planes
  - Z=0 (Symmetry Plane)
  - $X=33.8D_j$
- At the intersection of these Planes
  - All Reynolds Stresses and Mean Velocity Gradients are available
- Evaluate Effective Eddy Viscosity
  - Ratio of Measured Reynolds Stresses to Model Form of Strain Terms
  - If Model should work, these should yield same ratios for each Reynolds Stress Component.

$$-\overline{u_i' u_j'} = 2\nu_T\left[S_{ij} - \frac{1}{3}\delta_{ij}S_{kk}\right] - \frac{2}{3}k\delta_{ij}$$

$$\nu_T = \frac{-\overline{u_i' u_j'} + \frac{2}{3}k\delta_{ij}}{2\left[S_{ij} - \frac{1}{3}\delta_{ij}S_{kk}\right]}$$

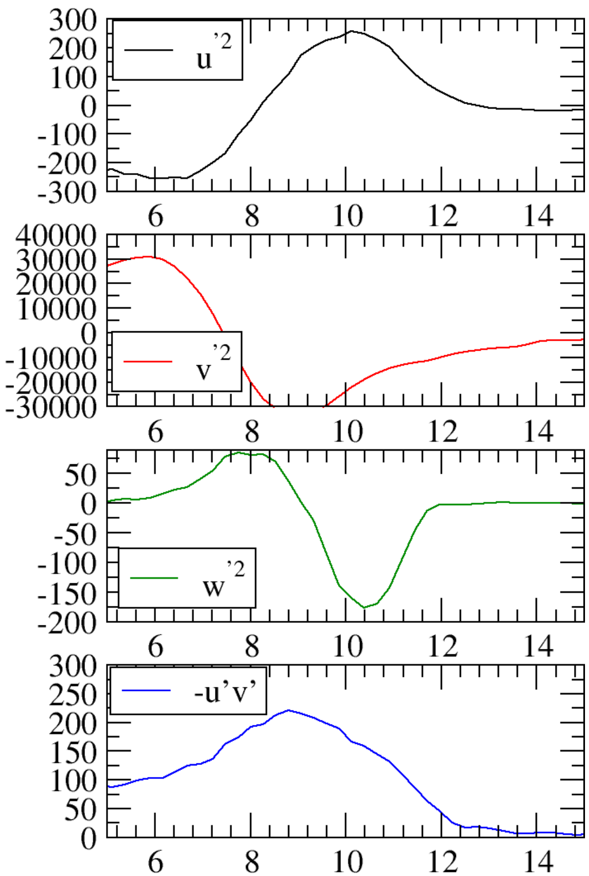


Cross Plane PIV

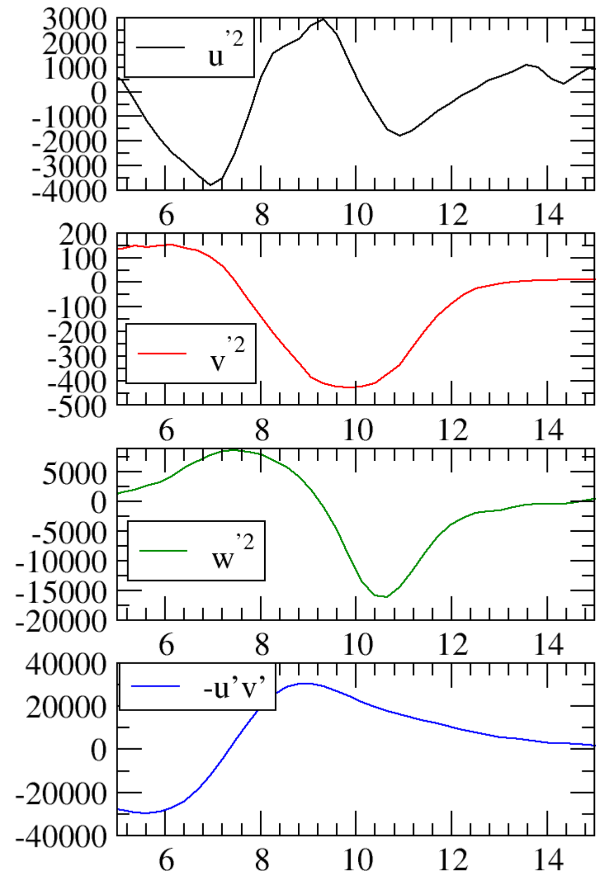


Symmetry Plane PIV

Analysis of Experimental Data



$$-\overline{u_i' u_j'} + \frac{2}{3}k\delta_{ij}$$



$$2\left[S_{ij} - \frac{1}{3}\delta_{ij}S_{kk}\right]$$

Analysis of Experimental Data

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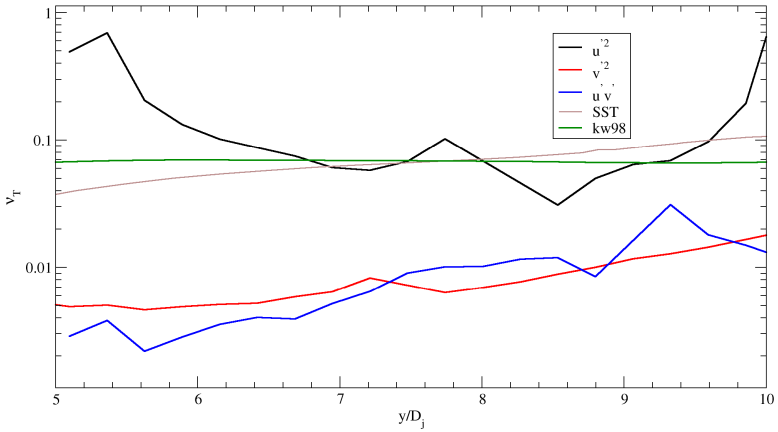
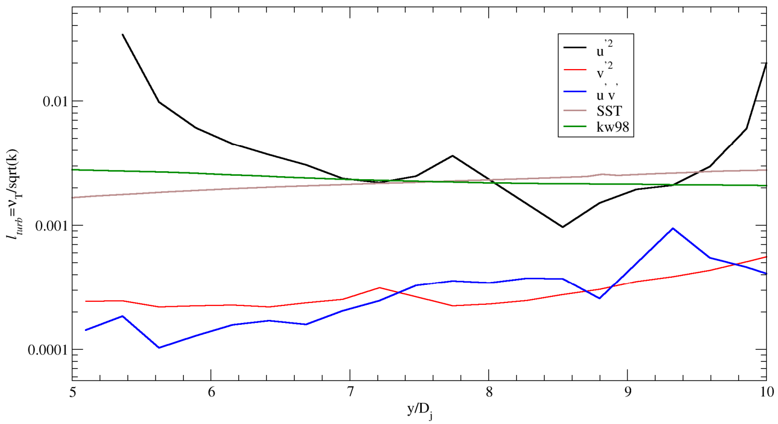
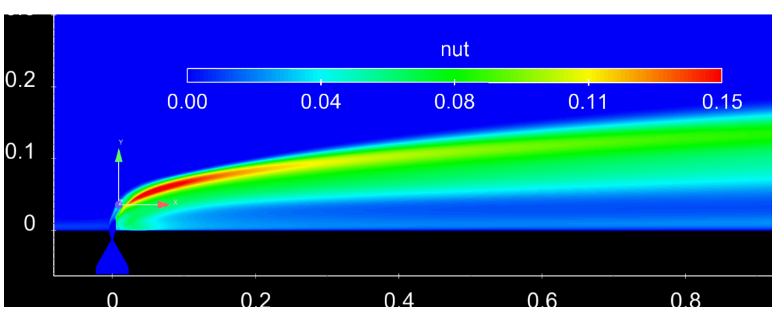
ν_T

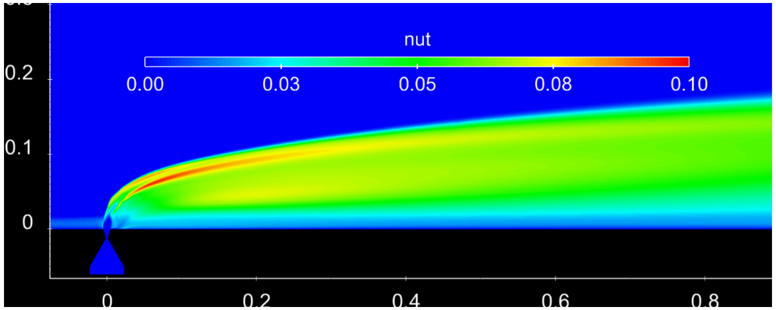


$$l_{turb} = \nu_T / \sqrt{k}$$





SST



KW98

Conclusions

- A detailed examination of two equation turbulence models for modeling of jet-in-crossflow problems has been presented
  - Primarily k-ω family of models (1998,2006 and SST variants)
  - Examination also included compressibility corrections by Wilcox.
  - Primary goal to examine how well they capture the CVP position and strength.
- Computational Results show that:
  - All the models qualitatively capture the gross features of the flow
  - None of the models quantitatively agree with measured values
    - Mean velocities, turbulent stress profiles have been compared in detail
  - All models over-predict mean velocity deficit in the jet
    - Under-predict mixing
  - All models predict vortex location to be too high
    - Momentum exchange between jet and cross flow is not captured
  - Performance of the model uniformly poor across jet momentum ratio and Mach number ranges examined.

Conclusions

- Detailed analysis of Boussinesq Approximation using experimental data has been carried out
  - The analysis shows that this approximation is not a good one for the flow considered
  - Large variability in the length scales of evolution for each Reynolds stress component
    - This class of models cannot capture all details of this flow field.
- Need models/approaches that can accommodate the large variations in the evolutions of the Reynolds stress components.
  - LES studies have shows better agreement with experimental data.
  - DES / Hybrid RANS-LES approaches will be examined in the future.
    - Cost effective option?