



Test Cases for NASA's Revolutionary Computational Aerosciences Technical Challenge

Part 1: Standard Test Cases for Separated Flows

Part 2: Standard Test Cases for Propulsion

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Introduction

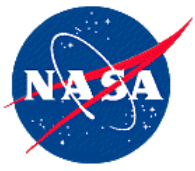
- Revolutionary Computational Aerociences (RCA) Technical Challenge*:
 - Identify and down-select critical turbulence, transition, and numerical method technologies for 40% reduction in predictive error against standard test cases for turbulent separated flows, evolution of free shear flows and shock-boundary layer interactions on state-of-the-art high performance computing hardware.
 - Timeframe: by 2017
- Discussions held with AIAA Turbulence Modeling Benchmark Working Group (TMBWG) and others
 - Ideas for good (representative) cases
 - Simple enough to be useful (avoid complex geometries that introduce uncertainties)
 - Possess the relevant flow physics
 - Ideas for evaluation metrics
 - By defining “common” cases and metrics, unbiased evaluation of future model improvements will be easier

* see: https://www.aeronautics.nasa.gov/fap/aeronautical_sciences.html

Introduction, cont'd



- Issue 1:
 - There are too many cases out there, and everyone has their own favorite
- Solution 1:
 - Highlight top 2-3 representative “primary” cases for each category, but list many others as optional
- Issue 2:
 - Many cases exist for which RANS “fails” but LES/DNS/hybrid “succeeds”
- Solution 2:
 - Interpret differently: For RANS, look for 40% improvement in results; for LES/DNS/hybrid, look for dramatic improvement in time-to-solution for those cases where the prediction is already good
- Issue 3:
 - Impossible to agree on metrics; they are either too simplistic or too difficult to define
- Solution 3:
 - Define some relevant metrics for the primary cases, but allow some leeway and use judgment



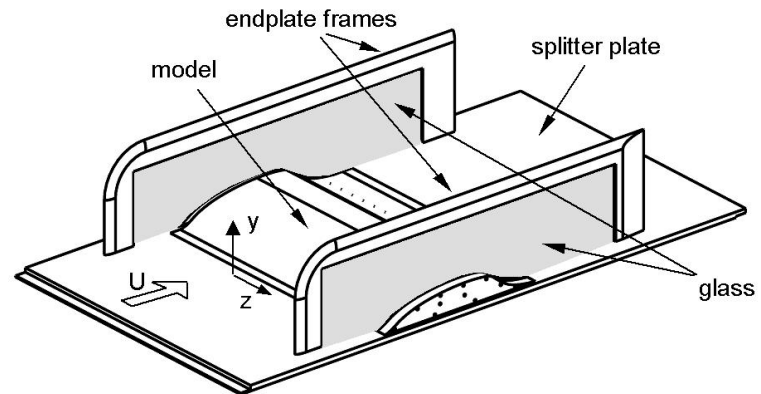
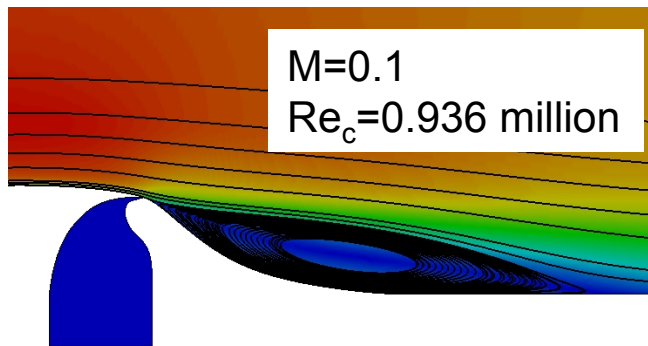
Separated Flow Cases

2-D NASA Hump

Greenblatt et al



- Rationale for: excellent high-quality reference experimental data set; good 2-D characteristics; includes both baseline and flow control; RANS known to do poorly; eddy-resolving methods have been shown to do well; well-vetted in previous workshop
- Rationale against: endplates introduced some blockage

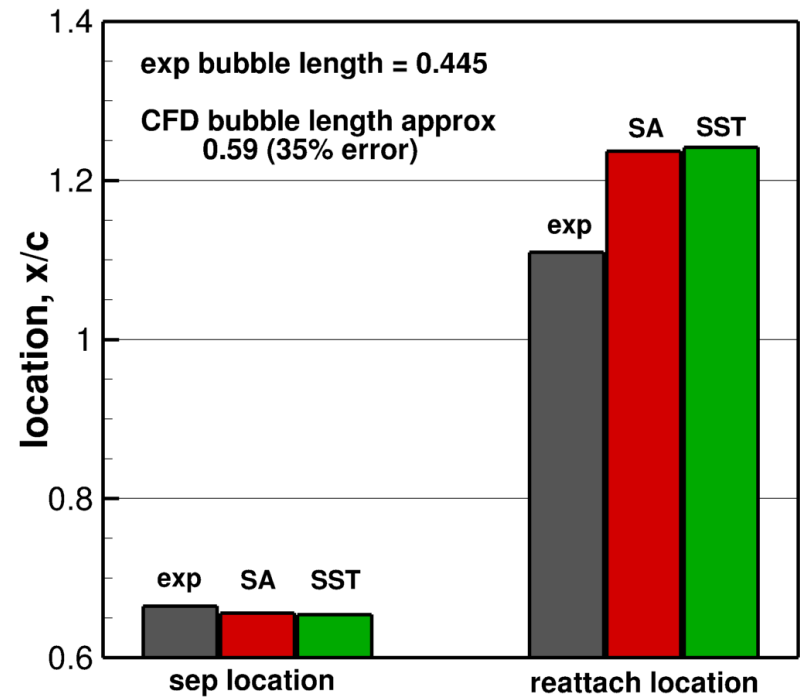
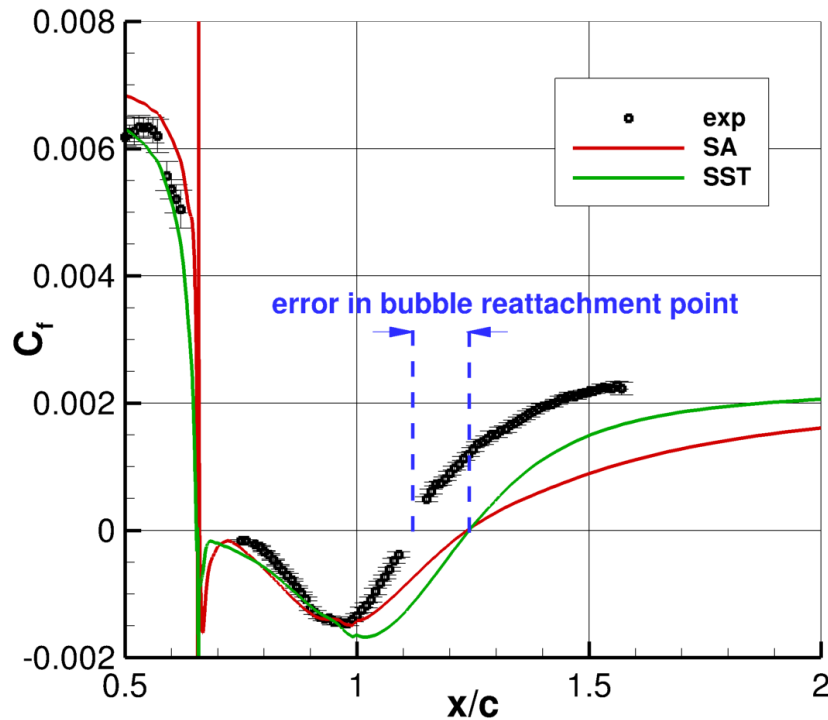


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- Rumsey, C. L., "**Turbulence Modeling Resource**," <http://turbmodels.larc.nasa.gov> (data posted online), and "**CFD Validation of Synthetic Jets and Turbulent Separation Control**," <http://cfdval2004.larc.nasa.gov> (data posted online).

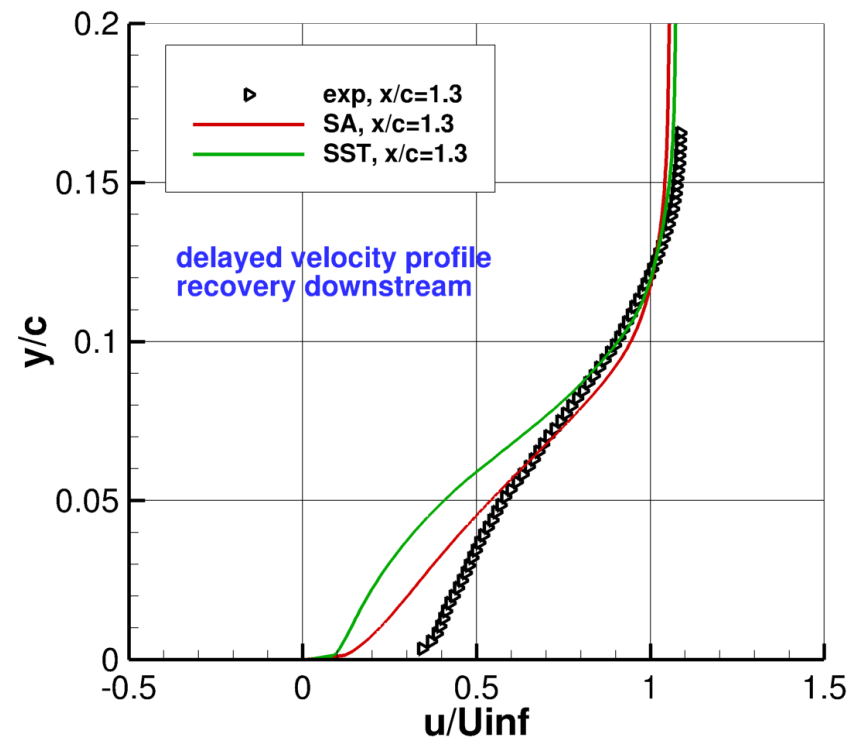
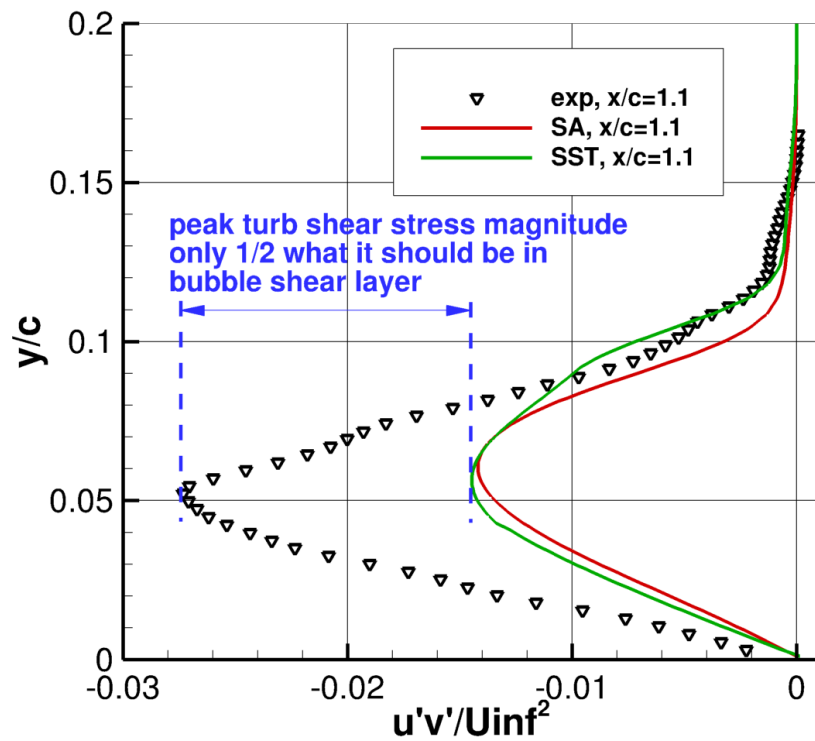
2-D NASA Hump (cont'd)

Baseline case: Typical RANS 35% error in bubble size (overprediction)



2-D NASA Hump (cont'd)

Baseline case: Typical RANS turbulent shear stress too small in magnitude in separated shear layer of bubble





2-D NASA Hump (cont'd)

- General validation metrics:
 - Separation and reattachment locations
 - Turbulent shear stress profiles
 - Velocity profiles
 - Surface pressure and skin friction coefficients

- Specific validation metrics:

$$((x / c)_{sep} - 0.665) / 0.665$$

$$((x / c)_{reattach} - 1.1) / 1.1$$

$$-\left[(u'v' / U_{ref}^2)_{\min@x/c=0.8} + 0.020\right] / 0.020$$

- From first two, can find bubble size relative to experiment
- Current typical RANS for baseline case:

$$\left[\left\{(x / c)_{reattach} - (x / c)_{sep}\right\} - 0.435\right] / 0.435 \approx 35\%$$

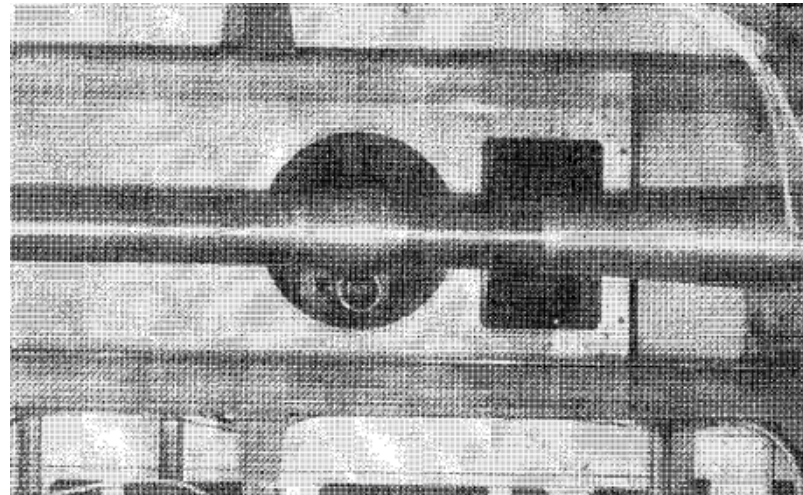
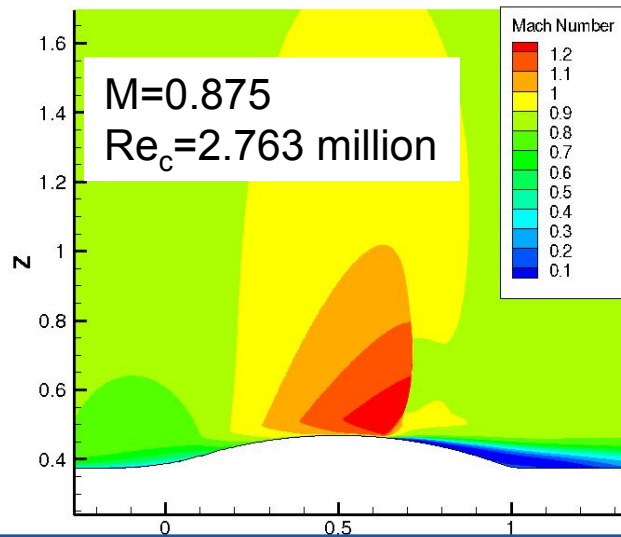
$$-\left[(u'v' / U_{ref}^2)_{\min@x/c=0.8} + 0.020\right] / 0.020 \approx -45\%$$

Axisymmetric Transonic Bump

Bachalo & Johnson



- Rationale for: includes shock-induced separation; widely-used dataset for many years; axisymmetry removes 2-D questions; RANS OK for some aspects but poor for others
- Rationale against: old experiment; no experience yet with eddy-resolving methods

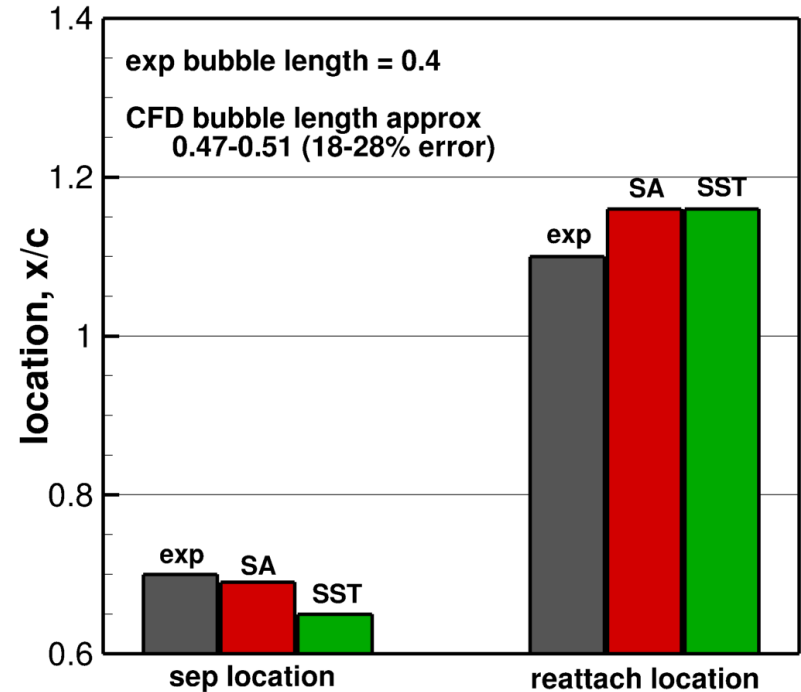
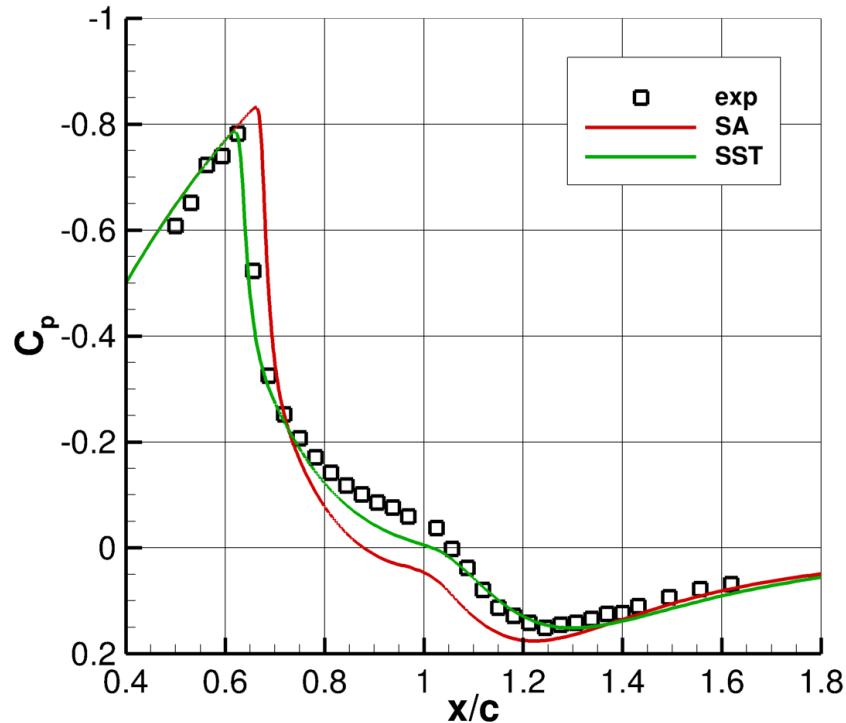


- Bachalo, W. D., Johnson, D. A., "Transonic, Turbulent Boundary-Layer Separation Generated on an Axisymmetric Flow Model," AIAA Journal, vol. 24, no. 3, pp. 437-443, 1986.
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Axisymmetric Transonic Bump (cont'd)



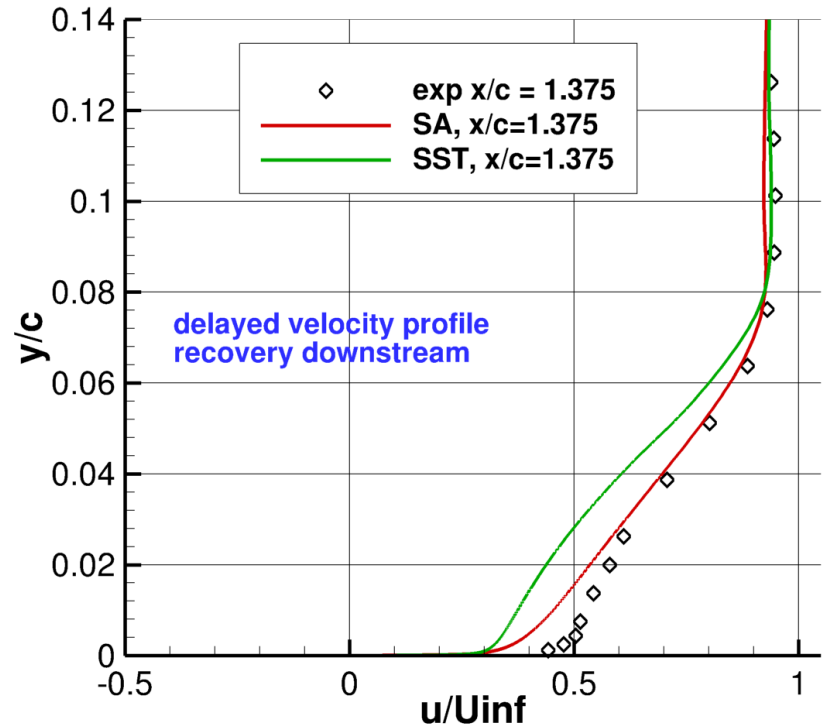
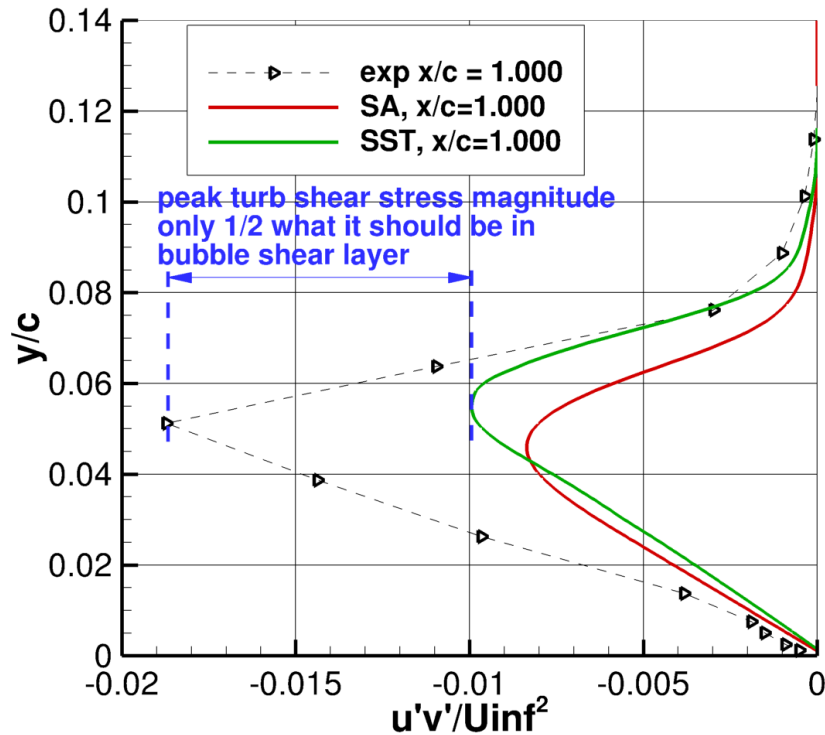
Typical RANS: C_p can be reasonable, but 20-30% error in bubble size (overprediction)



Axisymmetric Transonic Bump (cont'd)



Typical RANS: turbulent shear stress too small in magnitude
in separated shear layer of bubble



Axisymmetric Transonic Bump (cont'd)



- General validation metrics:
 - Separation and reattachment locations
 - Turbulent shear stress profiles
 - Velocity profiles
 - Surface pressure coefficients

- Specific validation metrics:

$$((x / c)_{sep} - 0.7) / 0.7$$

$$((x / c)_{reattach} - 1.1) / 1.1$$

$$-\left[(u'v' / U_{ref}^2)_{\min@x/c=1.0} + 0.019\right] / 0.019$$

- From first two, can find bubble size relative to experiment
- Current typical RANS:

$$\left[\left\{(x / c)_{reattach} - (x / c)_{sep}\right\} - 0.4\right] / 0.4 \approx 25\%$$

$$-\left[(u'v' / U_{ref}^2)_{\min@x/c=1.0} + 0.019\right] / 0.019 \approx -50\%$$

Additional Optional Separated Cases



- 2-D Wake flow in APG (Driver & Mateer, 2002)
- 2-D Transonic Diffuser (Sajben, 1983)
- 2-D Ramp flow (Cuvier et al, 2014)
- 2-D Periodic Hill (Almeida et al, 1993; Frohlich et al, 2005)
- 2-D Planar Asymmetric Diffuser (Buice & Eaton, 2000)
- 2-D NACA 4412 at high AoA (Coles & Wadcock, 1979 & 1987)
- 2-D Curved Backward-Facing Step (Bentaleb et al, 2012)
- 2-D Separated Channel flow (Marquillie et al, 2008)



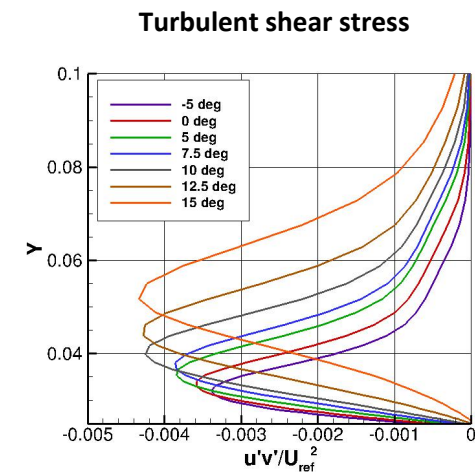
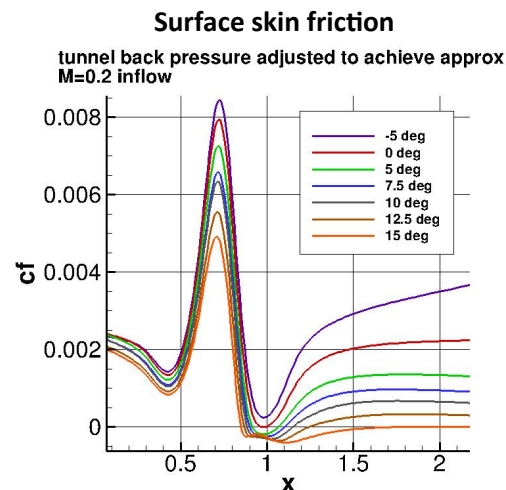
Additional Optional Separated Cases

- 3-D Axisymmetric Hill (Byun & Simpson, 1996)
- 3-D FAITH Hill (Bell et al, 2006)
- 3-D Cherry Diffuser (Cherry et al, 2008)
- 3-D ONERA M6 Wing (Schmitt & Charpin, 1979)
- 3-D NASA Trapezoidal Wing (Johnson et al, 2000)
- 3-D Common Research Model (Rivers et al, 2012)
- 3-D Wing-body-juncture (Devenport & Simpson, 1992)
- 3-D Prolate Spheroid (Chesnakas & Simpson, 1996)

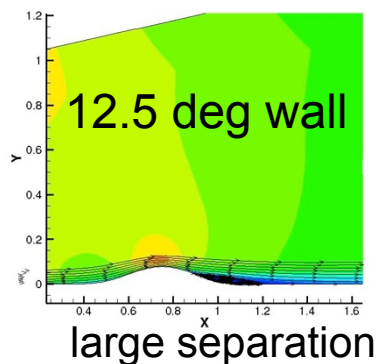
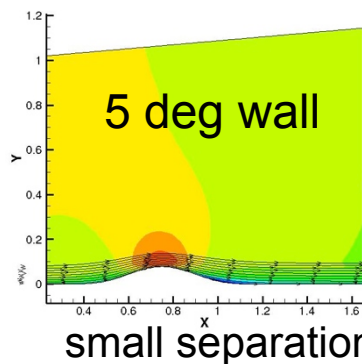
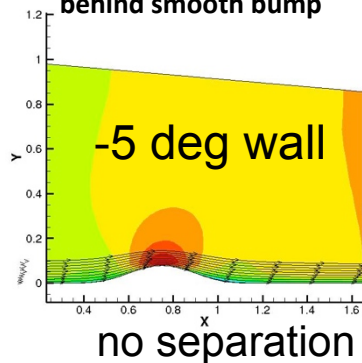
Proposed Fundamental Experiments Investigating Separation Onset and Progression



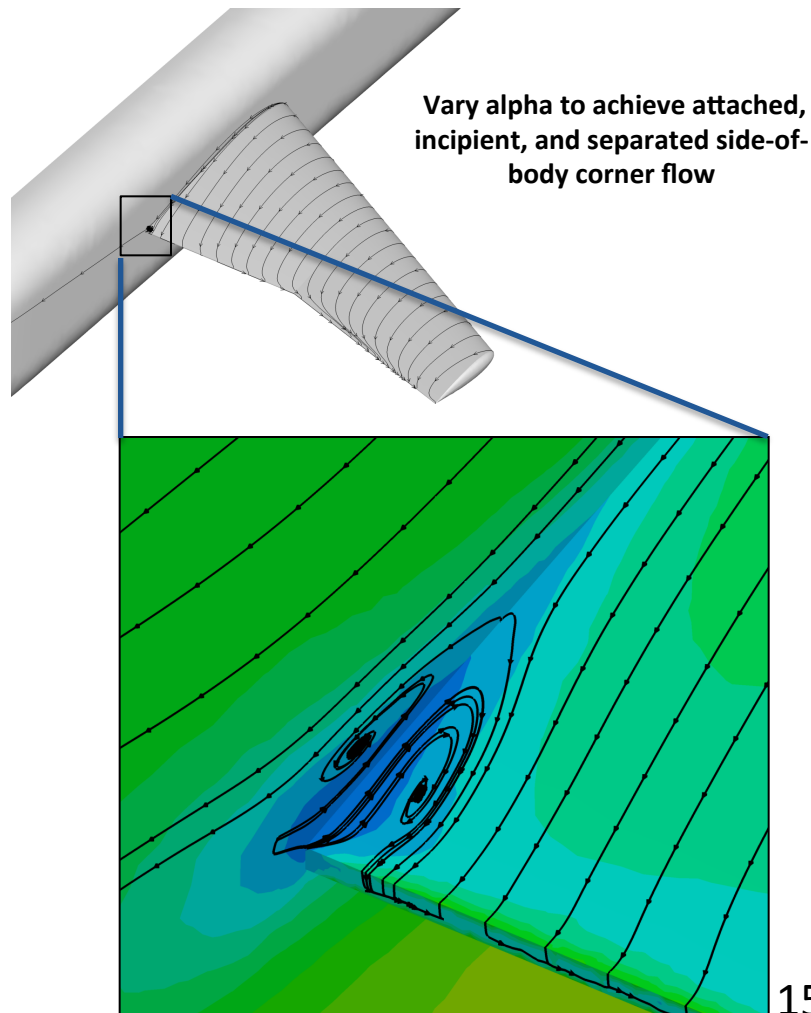
Axisymmetric Bump



Plots showing effect of top wall shape on separation bubble behind smooth bump



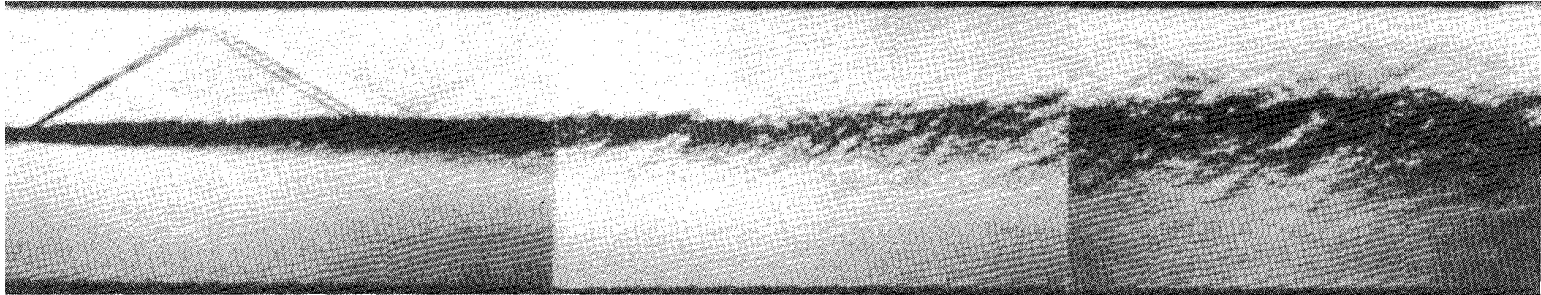
3-D Juncture Flow





Propulsion Cases

Compressible Mixing Layer



- Goebel, Dutton, & Gruber
Univ. of Illinois
- Two convective Mach numbers
 - Case 2, $M_c = 0.46$
 - Case 4, $M_c = 0.86$
- Data
 - LDV
 - Mean velocities
 - Reynolds stresses
 - Growth rates
 - Schlieren

- Goebel, S.G. and Dutton, J.C., "Experimental Study of Compressible Turbulent Mixing Layers," AIAA Journal, vol. 29, no. 4, pp. 538-546, April, 1991

- *Goebel, S.G. "An Experimental Investigation of Compressible Turbulent Mixing Layers," Ph.D. Thesis, Dept. of Mech. and Ind. Eng., Univ. of Illinois., Urbana, Ill., 1990.

- Gruber, M.R. and Dutton, J.C., "Three-Dimensional Velocity Measurements in a Turbulent Compressible Mixing Layer," AIAA Paper 92-3544, July 1992.

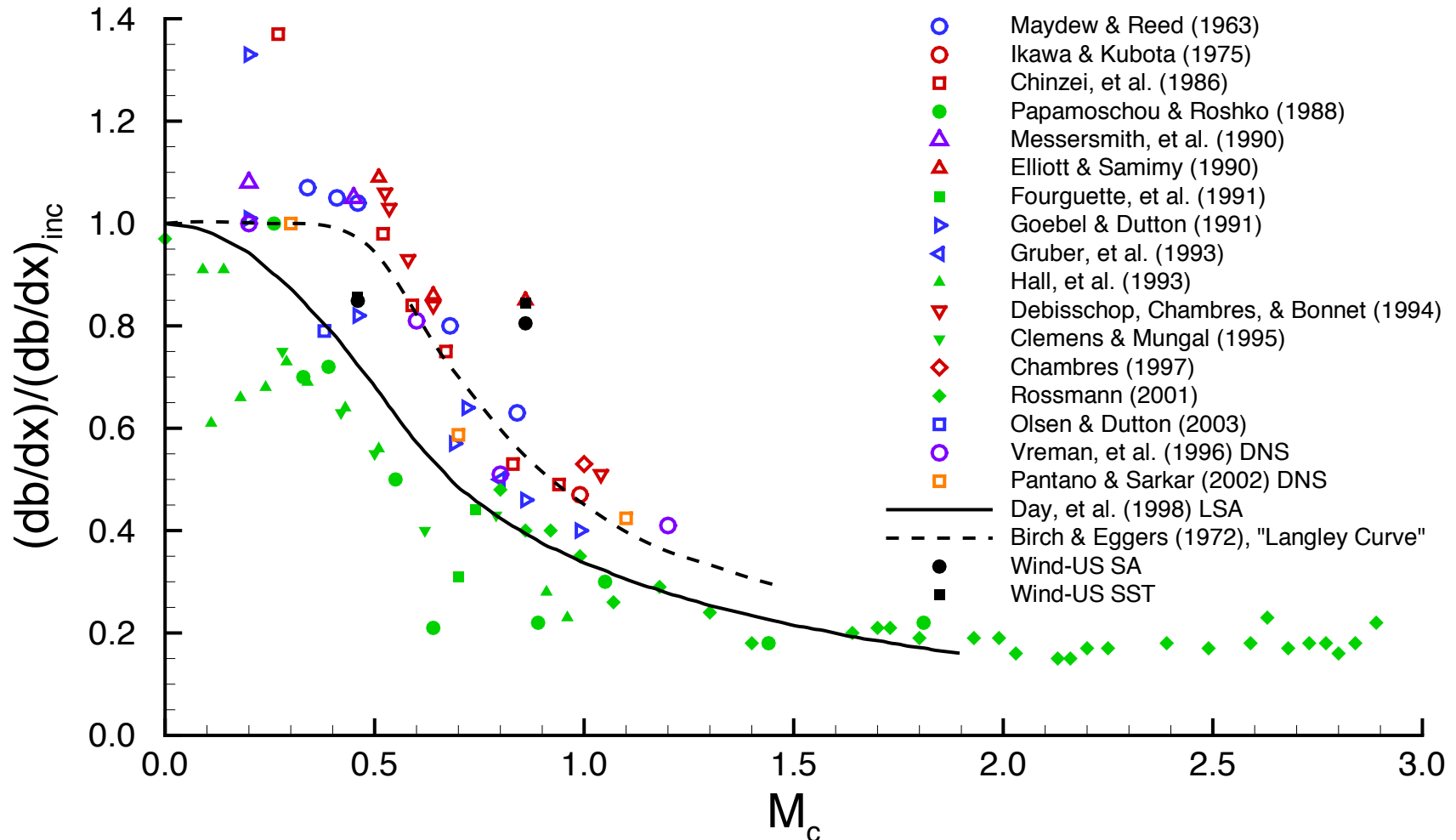


Compressible Mixing Layer

- Objective: Improve the prediction of shear layers, including the developing region, and the effect of compressibility
- Metrics
 - Growth rate
 - Mean velocity fields
 - Reynolds stress fields
- Rationale for
 - Comprehensive data set for M_c s from 0.2 to 1.0
 - 2-component LDV, with some 3-component LDV and PIV
 - Data compares well against historical measurements
- Rationale against
 - High M_c case difficult to converge
 - Tunnel wall effects, blockage and shock reflections are present
- Need new experiment?

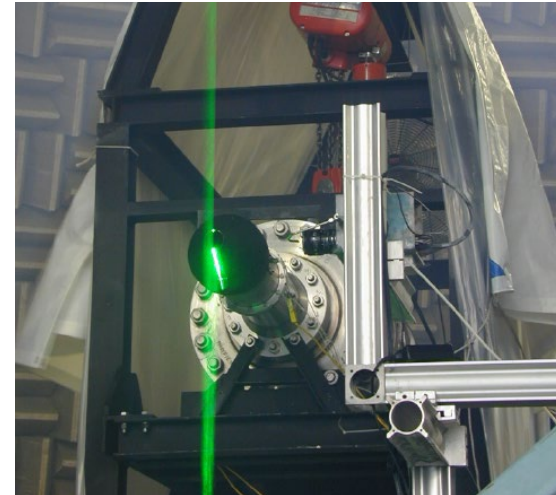
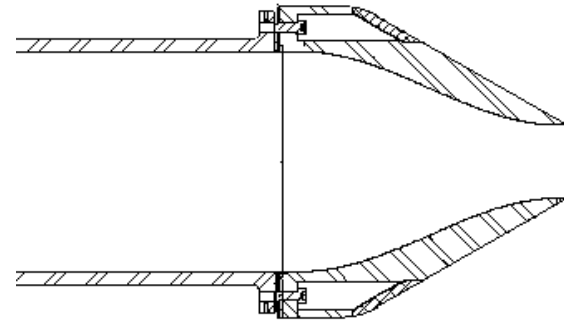
Compressible Mixing Layer

Growth Rate



Round Jet

- Bridges & Wernet, NASA Glenn
- Three test conditions
 - Set point 3, Mach 0.5 cold
 - Set point 23, Mach 0.5 hot
 - Set point 7, Mach 0.9 cold
- Data
 - Temporally resolved PIV data
 - Mean velocities
 - Reynolds stresses
 - Farfield noise



- Brown, C.A., and Bridges, J., "Small Hot Jet Acoustic Rig Validation," NASA TM-214234, April, 2006.
- *Bridges, J., Wernet, M.P., "The NASA Subsonic Jet Particle Image Velocimetry (PIV) Dataset," NASA TM 2011-216807, Nov. 2011
- Bridges, J. and Wernet, M.P., "Validating Large-Eddy Simulation for Jet Aeroacoustics," Journal of Propulsion and Power, vol. 28, no. 2, pp. 226-234, March-April, 2012.

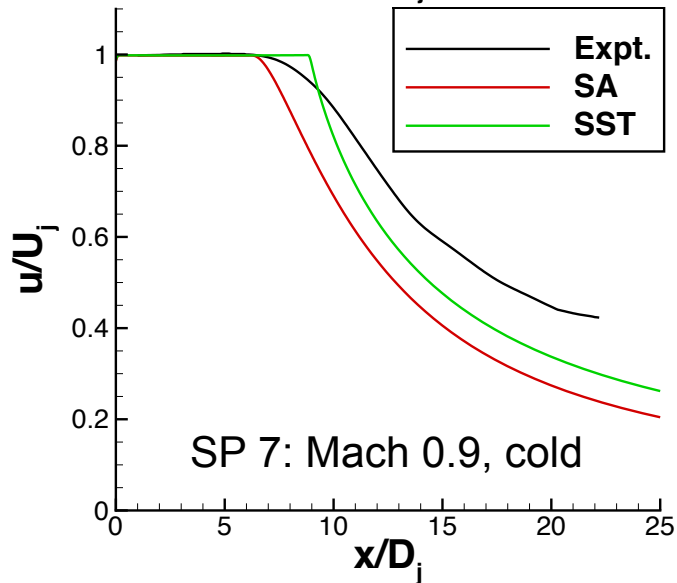
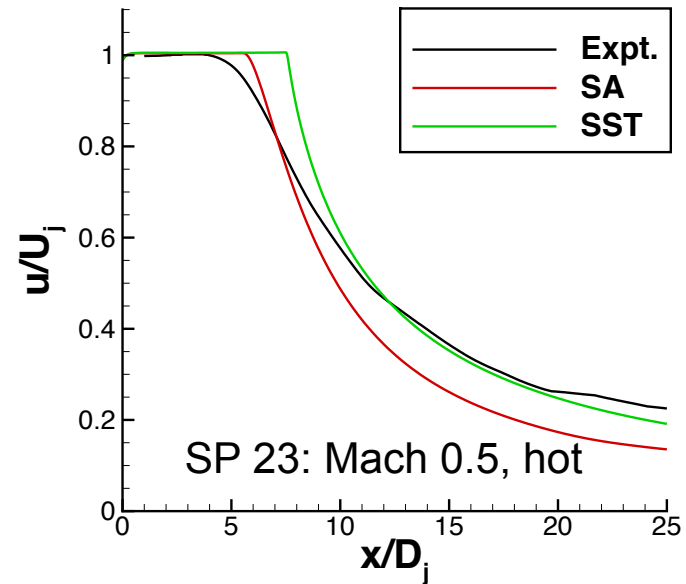
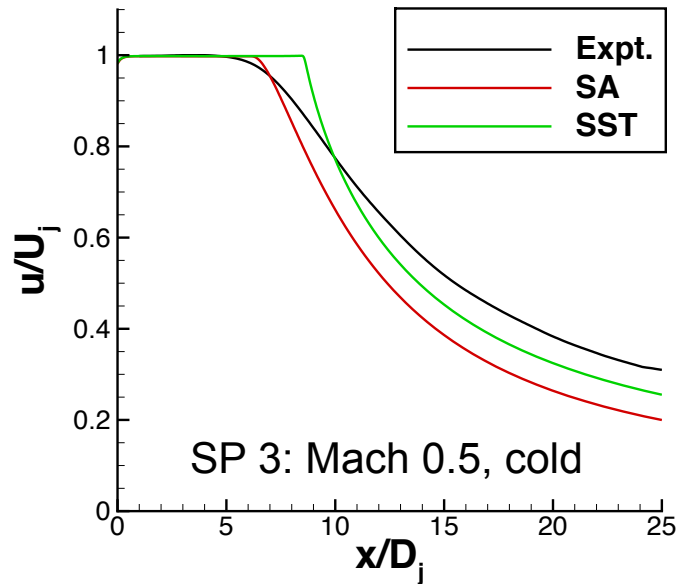


Round Jet

- Objective: Improvement the prediction of jets, including the developing region, the effect of compressibility, and the effect of temperature.
- Metrics
 - Location of the end of the inviscid core flow (the point where $u/U_{jet} = 0.98$)
 - Value and location of the peak turbulent kinetic energy on the jet centerline.
 - Mean velocity fields
 - Reynolds stress fields
- Rationale for
 - Data already widely used for validation (de facto standard jet data set)
 - Data compares against historical measurements
- Rationale against
 - Nozzle boundary layer and/or initial jet profile not defined

Round Jet

Centerline Mean Velocities



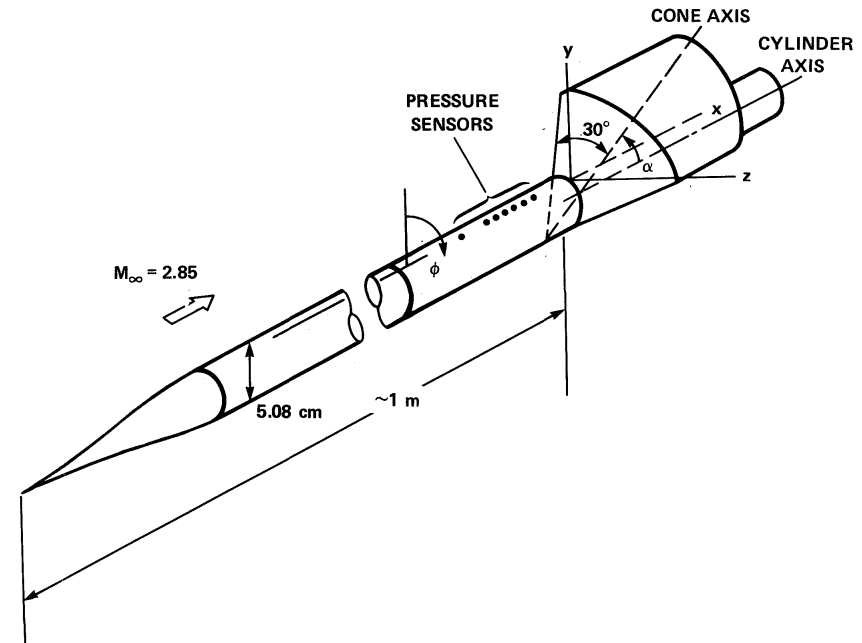
Set Point	Expt.	SA	%err	SST	%err
3	6.3	6.73	6.83	8.67	37.6
7	7.8	6.84	-12.3	9.01	15.5
23	5.0	6.00	20.0	7.65	53.0

End of inviscid core, x/D_j

Shock Wave Boundary Layer Interaction

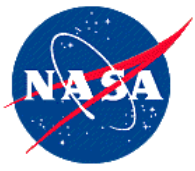


- J. Brown et al, NASA Ames
- Axisymmetric compression corner
- Mach 2.85
- 30 deg. conical flare
- Data
 - LDV
 - Mean velocities
 - Reynolds stresses
 - Surface static pressures
 - Interferometry
 - Schlieren



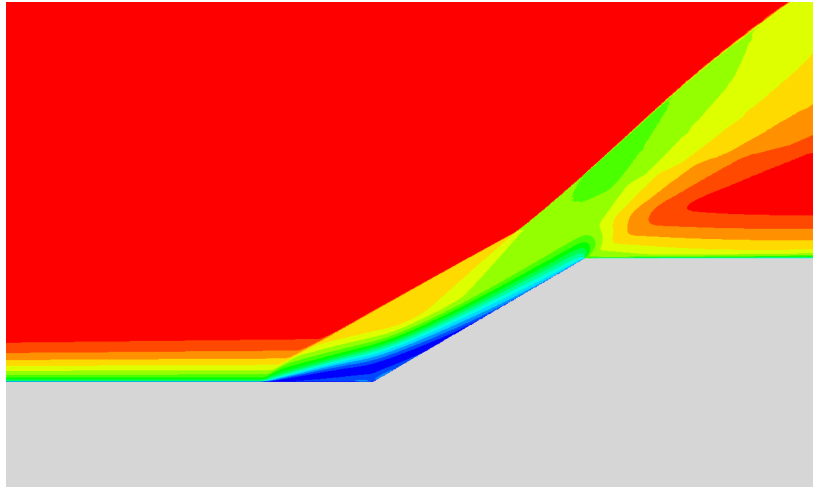
- Dunagan, S.E., Brown, J.L. and Miles, J.B. ,” Interferometric Data for a Shock/Wave Boundary-Layer Interaction,” NASA TM 88227, Sept. 1986.
- Brown, J.D., Brown, J.L. and Kussoy, M.I., “A Documentations of Two- and Three-Dimensional Shock-Separated Turbulent Boundary Layers,” NASA TM 101008, July, 1988.
- *Settles, G.S., and Dodson, L.J., “Hypersonic Shock/Boundary-Layer Interaction Database NASA CR 177577, April 1991
- Wideman, J., Brown, J., Miles, J., and Ozcan, O., “Surface Documentation of a 3-D Supersonic Shock-Wave/Boundary-Layer Interaction,” NASA TM 108824, 1994

Shock Wave Boundary Layer Interaction



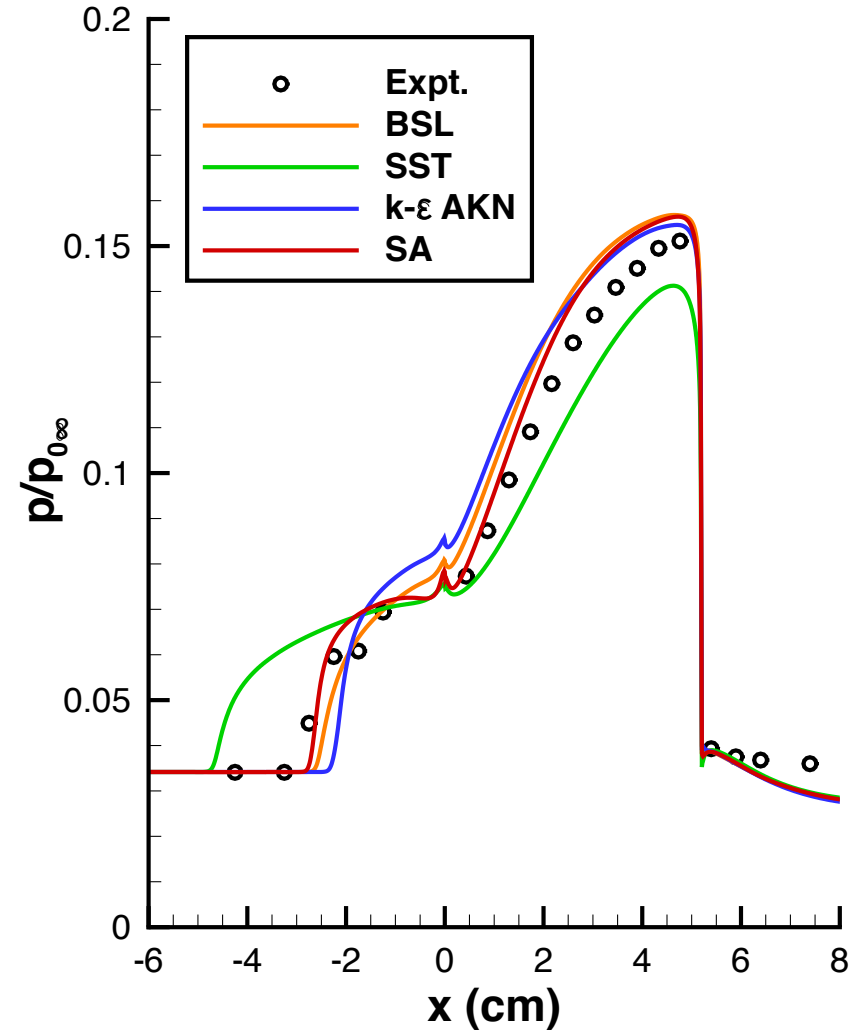
- Objective: Improve the prediction of shock boundary layer interaction including the extent of separation and the Reynolds stresses
- Metrics
 - Separation and reattachment locations, and separation length
 - Surface pressure coefficient
 - Velocity profiles
 - Reynolds stress profiles
- Rationale for
 - Simple geometry
 - Absence of corner flows found in many SWBLI experiments
 - Reynolds stresses available
- Rationale against
 - Separation onset and pressure distributions are already well predicted by some RANS models
 - Cusped nose of model not defined; effect is assumed negligible

Shock Wave Boundary Layer Interaction



Mach number contours

	Separation pt. (cm)	Reattach pt. (cm)	Length (cm)
Expt.	-2.73	0.97	3.70
BSL	-2.50	1.38	3.88
SST	-4.57	2.54	7.11
k-ε	-2.21	1.13	3.33
SA	-2.68	2.27	4.92

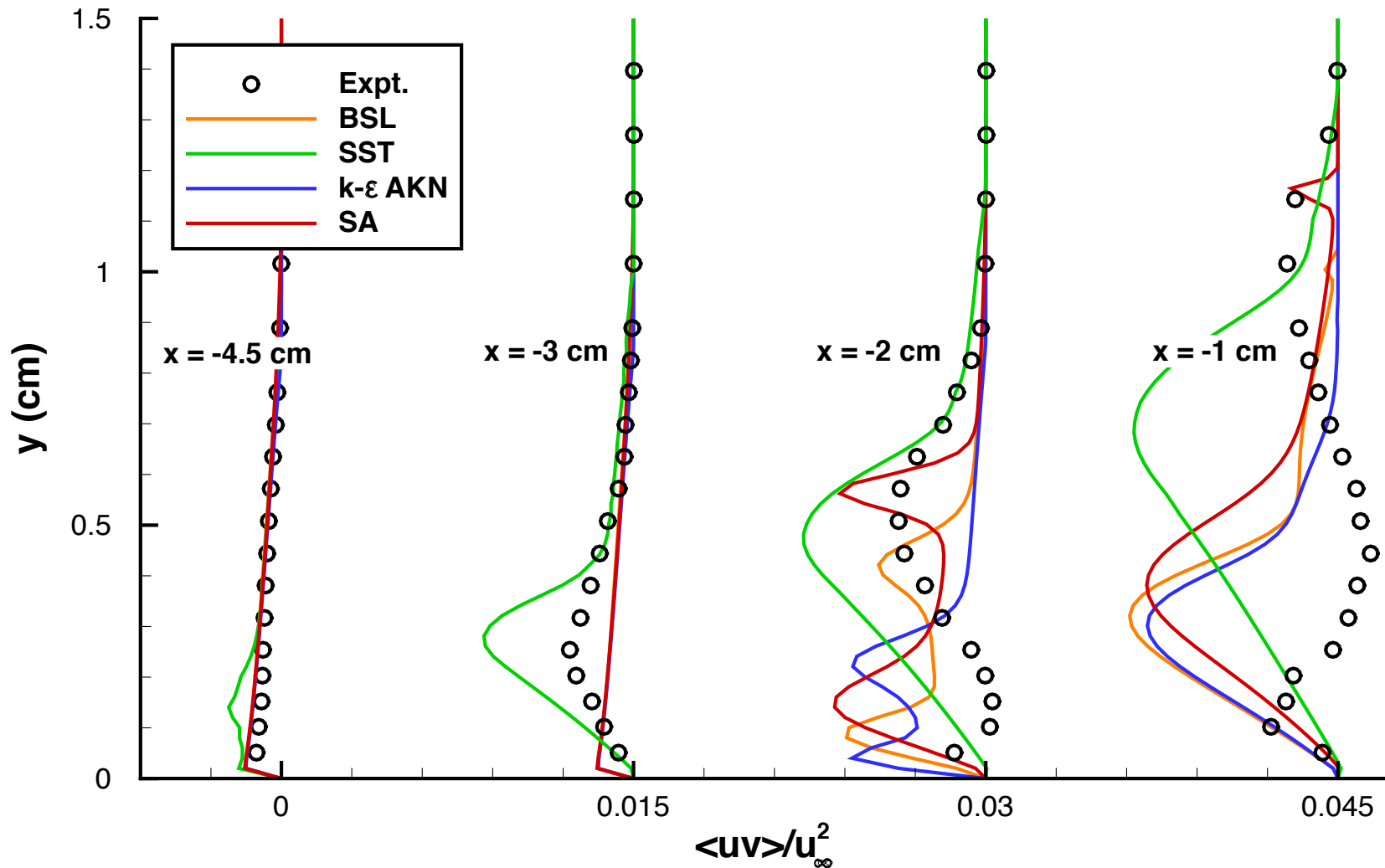


Surface static pressure

Shock Wave Boundary Layer Interaction



Shear Stress Profiles





Additional/Optional Cases

- Shear flows
 - Numerous shear layer cases
 - Seiner's Supersonic jet, $M_j = 2$ (Seiner et al, 1992)
 - Egger's Supersonic jet (Eggers, 1996)
- Shock-wave/boundary-layer interaction
 - Mach 2.25 Impinging SWBLI, UFAST (DuPont et al, 2008)
 - Mach 5 Impinging SWBLI (Schulein, 2004)
 - Mach 7 Axisymmetric Compression Corner (Kussoy & Horstman, 1989)
 - NASA GRC Mach 2.5 Axisymmetric Impinging SWBLI (Davis, TBD)

Turbulence CFD Validation Experiments (TCFDVE)

PROBLEM

Very few Shock Wave/Boundary-Layer Interaction (SWBLI) experiments reported in the open literature meet the rigorous criteria required to be considered as a CFD validation dataset. This is particularly true for experiments with detailed turbulence measurements.

OBJECTIVES

Obtain mean and turbulence quantities through a $M=2.5$ SWBLI of sufficient quantity and quality to be considered as a CFD validation dataset. Initial efforts will focus on a Mach 2.5 2-D (in the mean) interaction with follow-on efforts investigating 3-D interactions. Both attached and separated interactions will be considered.

APPROACH

A new $M=2.5$ 17cm axisymmetric facility is being constructed to investigate SWBLIs. The facility will be located in Test Cell W6B at NASA GRC. The SWBLI is generated by a cone located on the centerline of the facility. The strength of the interaction is varied by changing the cone angle. The measurement region of interest is where the conical shock interacts with the naturally occurring facility boundary-layer and is highlighted by the box shown in Figure 1. The new facility will be instrumented with conventional pressure instrumentation as well as hot-wire anemometry for measurement of turbulence quantities. Non-intrusive optical techniques such as PIV will be incorporated in the future. Test are also planned with dynamic surface shear film and fast response Pressure Sensitive Paint (PSP) in collaboration with Innovative Scientific Solutions, Incorporated (ISSI).

RESULTS

The new facility design is complete and delivery of the hardware is expected by the end of December 2014. Calibration of the facility is expected to commence in December. RANS and LES simulations of the facility are also underway at GRC.

SIGNIFICANCE

The data to be generated has been previously unavailable. Further, development of an in-house capability to investigate SWBLIs will allow CFD code developers and turbulence modelers to have direct input into the experiment. It will also allow the ability to revisit measurements if deemed necessary.

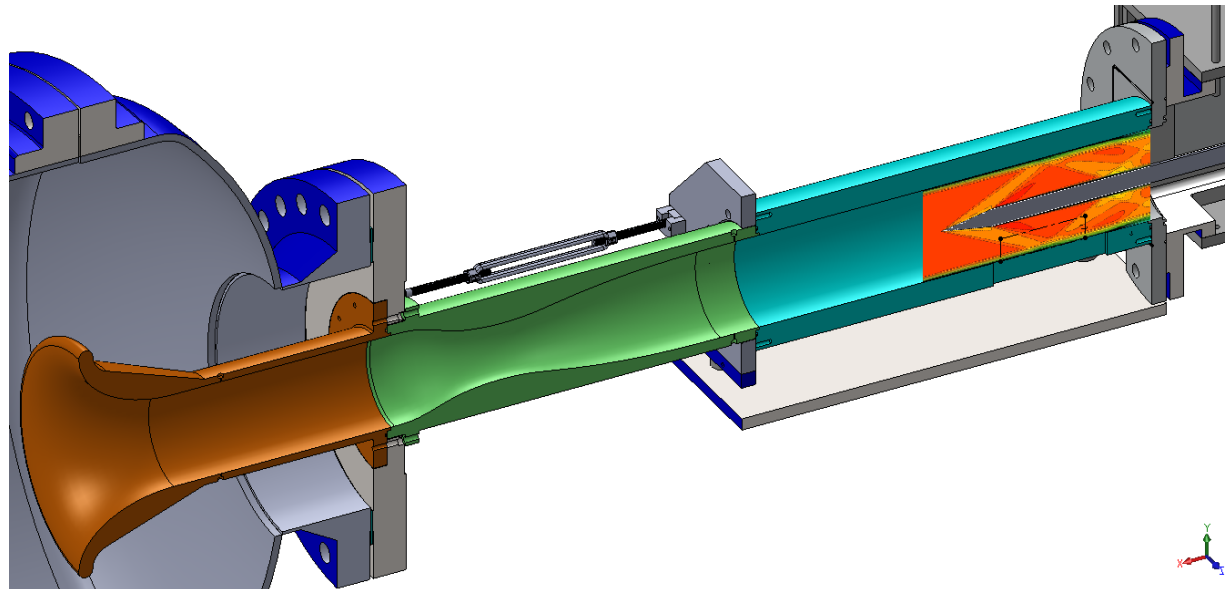


Figure 1. 17cm Axisymmetric Supersonic Wind Tunnel



Future Validation Needs

- Most of the primary test cases are old datasets
 - There have been significant advances measurement technology
 - New scale-resolving simulations require much more detailed boundary information
 - We have gained a better understanding of the requirements for validation experiments
- We believe there is a need for new validation data sets
 - What flows should be considered?
 - What quantities should be measured?
 - What are we missing?



Contact information

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