Status of Turbulence Modeling for High-Speed Propulsion Flow Problems

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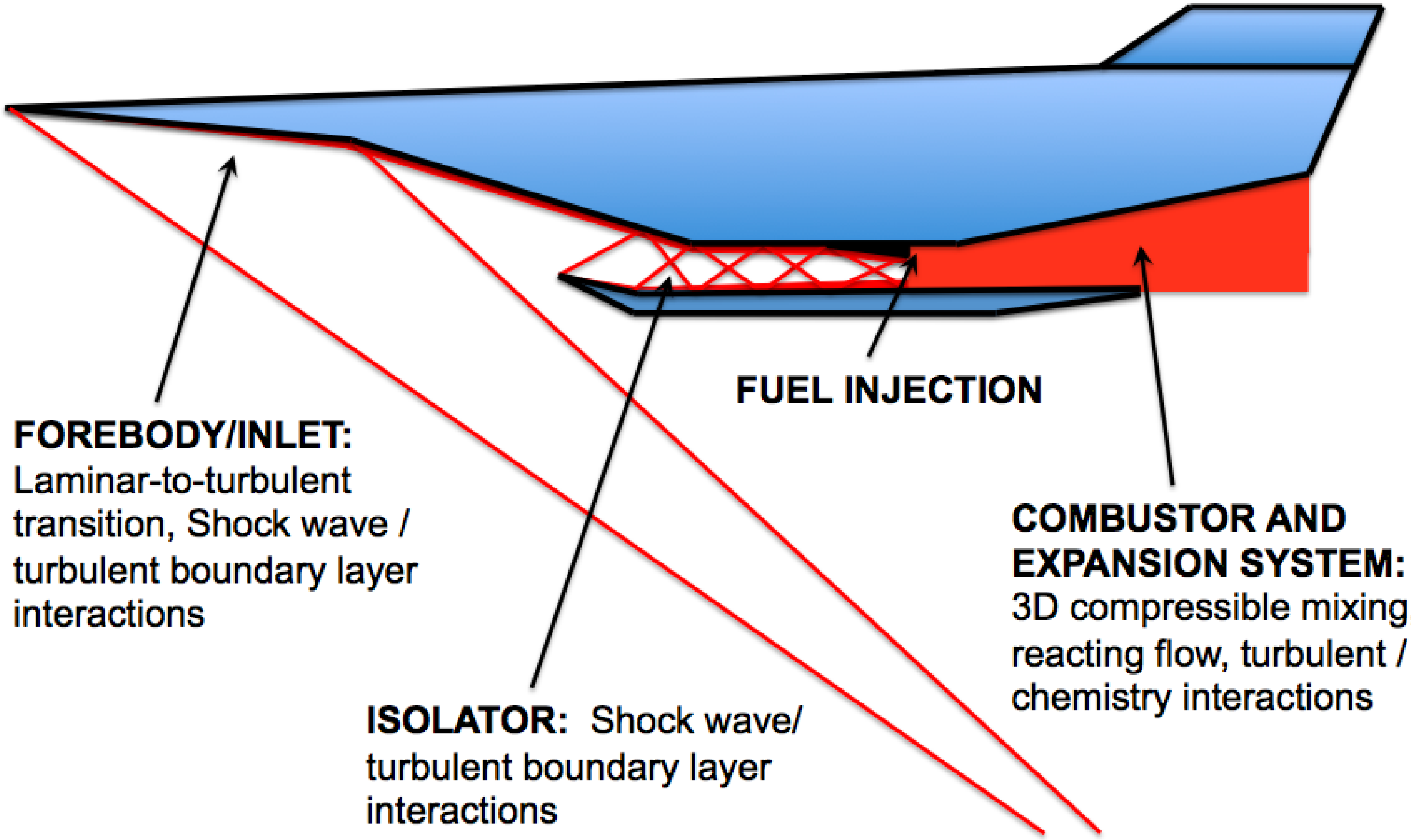
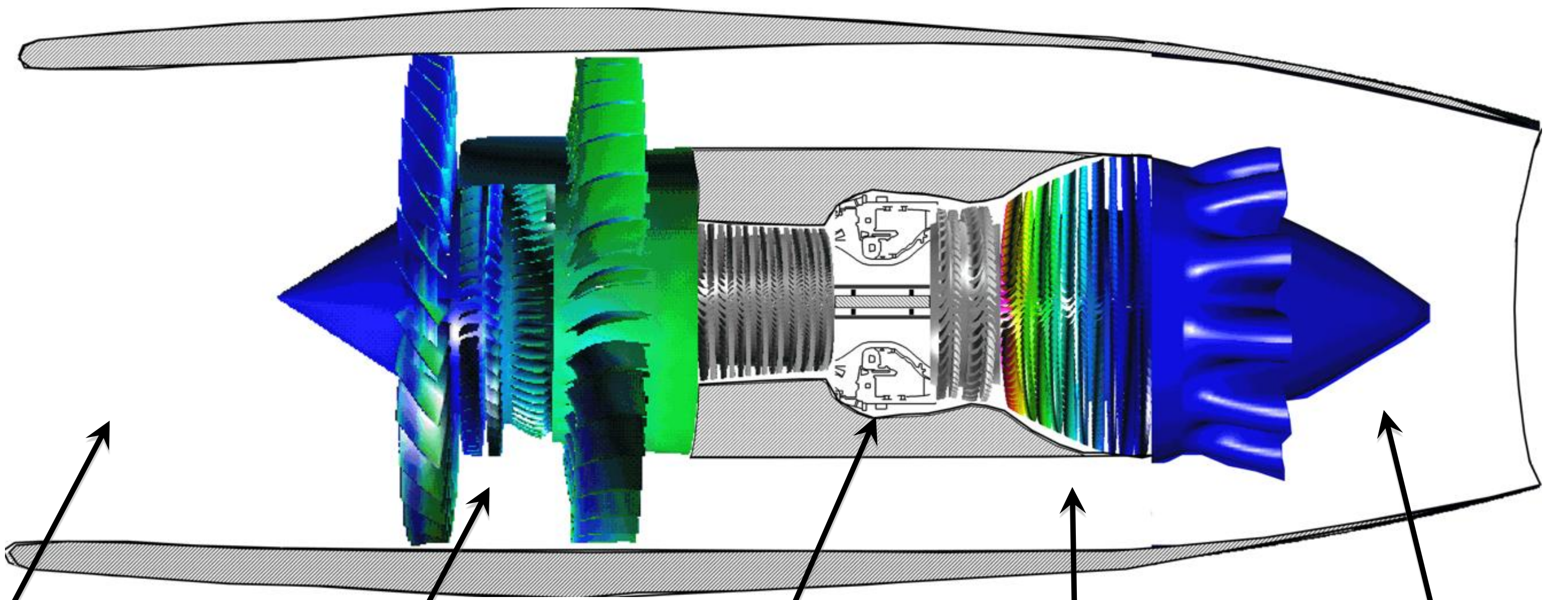
Introduction

- **An overview of key turbulence modeling areas for propulsion flows is presented.**
- **Emphasis is placed on "practical" state-of-the-art today:**
  - Standard practices using primarily RANS.
  - Promising new technology (i.e. LES, hybrid RANS/LES) that may be available for production use in near future.
  - Key shortfalls for which R&D is necessary.
- **Focus is placed on high-speed propulsion systems (i.e. scramjets); turbine engines are also addressed in less detail.**

Key Turbulent Features of Scramjet Flowpaths



Key Turbulent Features of Turbine Engine Flowpaths



INLET:
Transition, Separation

COMPRESSOR:
Swirling 3D flow, wakes, shock-interactions

COMBUSTOR:
3D reacting flow, turbulent / chemistry interactions, multi-phase

TURBINE:
Transition, 3D, very high heat transfer, film cooling

NOZZLE/MIXER, PLUME
3D Turbulent Mixing, Compressibility, Acoustics

Presentation Outline

- **Overview of Turbulence Modeling in Use for Propulsion Flows**
  - RANS
  - DNS and LES
- **Boundary Layer Transition – Inlets and Turbines**
- **3D Boundary Layer Effects**
- **Turbine Blade Heat Transfer**
- **Shock-Wave /Turbulent Boundary Layer Interactions**
- **Combustor / Reacting Flows**
  - Scalar Transport
  - Turbulent / Chemistry Interactions
- **Exhaust System Modeling**
  - Jet and Mixing - RANS
  - LES-based Methods
- **Experimental Validation Data Needs**
- **Conclusions**

RANS Turbulence Modeling

- Reynolds-Averaged Navier-Stokes (RANS) – replaces all unsteady turbulent motion with modeled turbulent stresses.
- Practical State of the art is two-equation models: k-ε , k-ω ,k-ζ. Menter Shear-Stress Transport (SST) is popular "hybrid model" combining k-ε and k-ω.
- For subsonic/transonic external aerodynamics, one equation models such as Spalart-Allmaras are popular – not used as much in propulsion flows.
- Full Reynolds-Stress Models – offer more complete representation of 3-D turbulent stress field, but have not lived up to promise in terms of improved predictions.
- Explicit algebraic stress models (EASMs) solve 2-eqn models, but used additional relations to obtain "Reynolds-stress-like" behavior.

Direct Calculation Methods

- **Direct Numerical Simulation (DNS) – calculate all turbulent scales down to the Kolmogorov scale – impractical for engineering flows.**
- **Large-Eddy Simulation (LES) – directly calculate largest scales and reserve modeling for smallest “subgrid-scale” stresses – active research showing promise in combustor and jet plume regions.**
- **Hybrid RANS/LES – has become popular in recent years – most effective use has been for flows where RANS can be used in attached boundary layers and LES away from walls.**
  - Demarcated or zonal hybrid RANS/LES – clear distinction is made between RANS and LES regions. Some physical mechanism is responsible for transition to turbulence. This was intent behind design of Detached Eddy Simulation (DES).
  - Continuous modeling – RANS and LES regions are not clearly separated – solution is expected to adjust, based on resolution. Desirable in theory, but difficult to achieve due to competing natures of RANS and LES.

Transition Modeling

- Several RANS-based models tried over the past several years – some solving additional transport equations for intermittency, Re_θ.
- Some success for flows with high freestream turbulence intensity – i.e. turbine cascades where bypass transition is dominant mechanism.
- Modal growth situations not easily represented by RANS-based techniques.
- Work shown here is with a model based on the Menter SST k-ω turbulence model, with transition modifications by Langtry, Sjolander, & Menter.
- Our work with the baseline published model indicated difficulties: (1) inability to reproduce experimentally observed transition, (2) significant grid sensitivity, (3) inability to become fully turbulent beyond transition. New formulation described in Denissen, Yoder, Georgiadis, NASA TM 2008-215451.

TKE equation

$$\frac{\partial \rho k}{\partial t} + \frac{\partial \rho U_j k}{\partial x_j} = PTM \cdot \mathcal{P}_k - \beta^* \rho \omega k + \frac{\partial}{\partial x_j}\left((\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right)$$

Modified model formulation:

$$PTM = 1 - 0.94(PTM1 + PTM2)\, F_3 \tanh\left((y^+/17)^2\right)$$

$$F_3 = e^{-\left(\frac{R_t}{3}\right)^2}(1 - P(R_t)) + \frac{1}{2}P(R_t)$$

$$P(R_t) = \frac{2.5}{\sqrt{2\pi}} e^{\frac{-(R_t-3)^2}{2}}$$

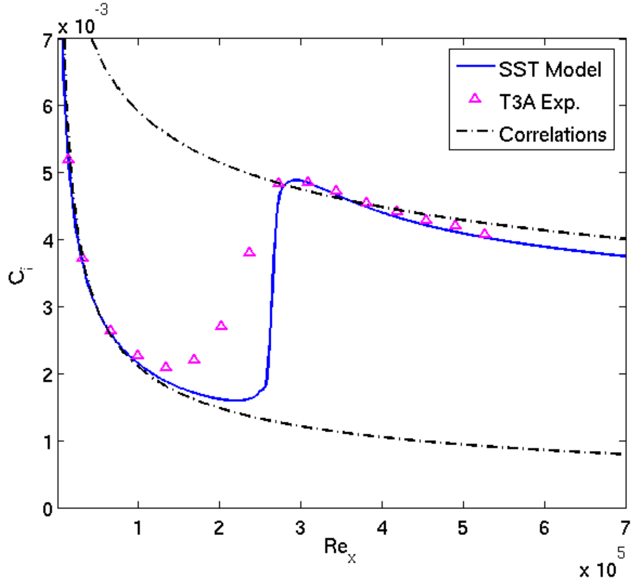
$$PTM1 = 1 - C_{PTM1} \begin{cases} [(3.28E-4)Re_v - (3.94E-7)Re_v^2 + (1.43E-10)Re_v^3]\,; & Re_v < 1000 \\ [0.12 + (1E-5)Re_v]\,; & Re_v > 1000 \end{cases}$$

Boundary Layer Transition Model Incompressible Validation

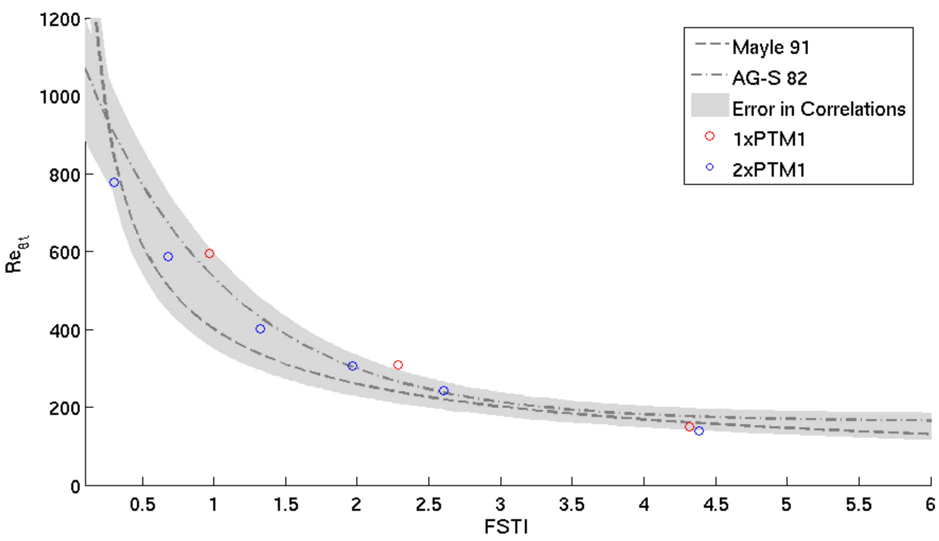
Incompressible Validation:

- Transition locations and skin friction examined for T3A benchmark data (ERCOFTAC)
- Several freestream intensities investigated.
- Grid sensitivity is high for incompressible cases.

C_f for FSTI = 2%



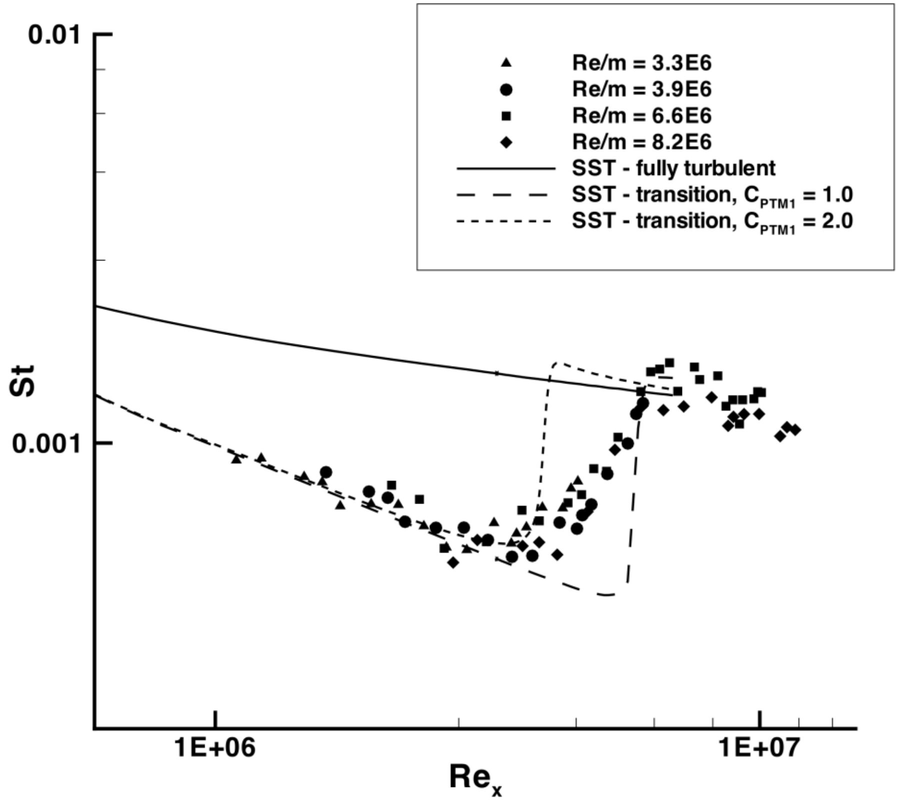
C_f Variation with FSTI



Boundary Layer Transition Model Hypersonic Validation

Hypersonic Validation:

- Mach 7.93, 7 degree straight cone investigated in AEDC Tunnel B, $T_w / T_o = 0.42$.
- Heat transfer measurements by Kimmel, JFE 1997.
- Integrated heat transfer: Transition-SST (6.7% error), Fully turbulent SST (18.5 % error).

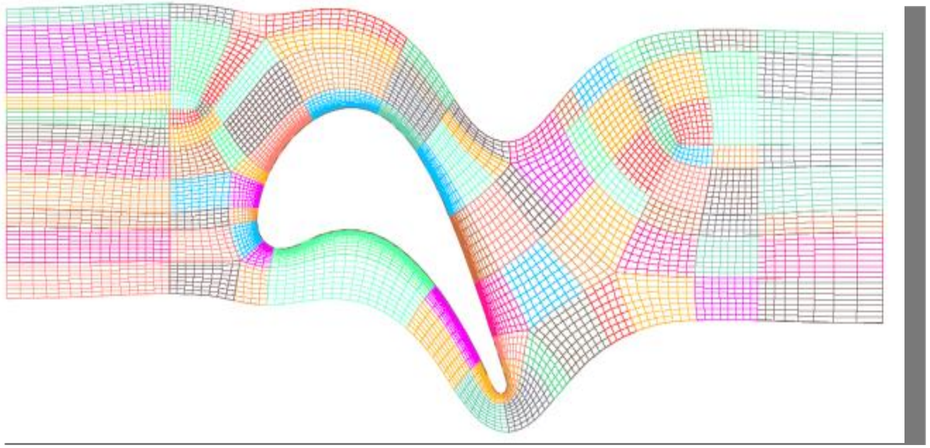


Turbine Bypass Transition Using the Walters-Leylek Model

- **k_L-k-ω models of Walters and Leylek**
- **Based on the earlier work of Mayle and Schulz on pre-transitional boundary layer. Transition occurs once k_L reaches a certain level.**
  - **k_L** is a wall phenomenon
  - Additional equation for **k_L**
- **Splat Mechanism (Bradshaw)**
  - Process by which eddies outside the boundary layer, having length scales of the order of δ, are brought to rest at the wall due to the impermeability condition, causing its energy to be redirected.
  - **Growth of k_L correlates with low-frequency normal (v′) fluctuations in F.S. turbulence. (Volino and Simon)**
  - **Splat mechanism responsible for growth of k_L(Volino).**

Figure: Courtesy of Ali Ameri, NASAGRC/OSU

2-D Blade Heat Transfer (WL Model)



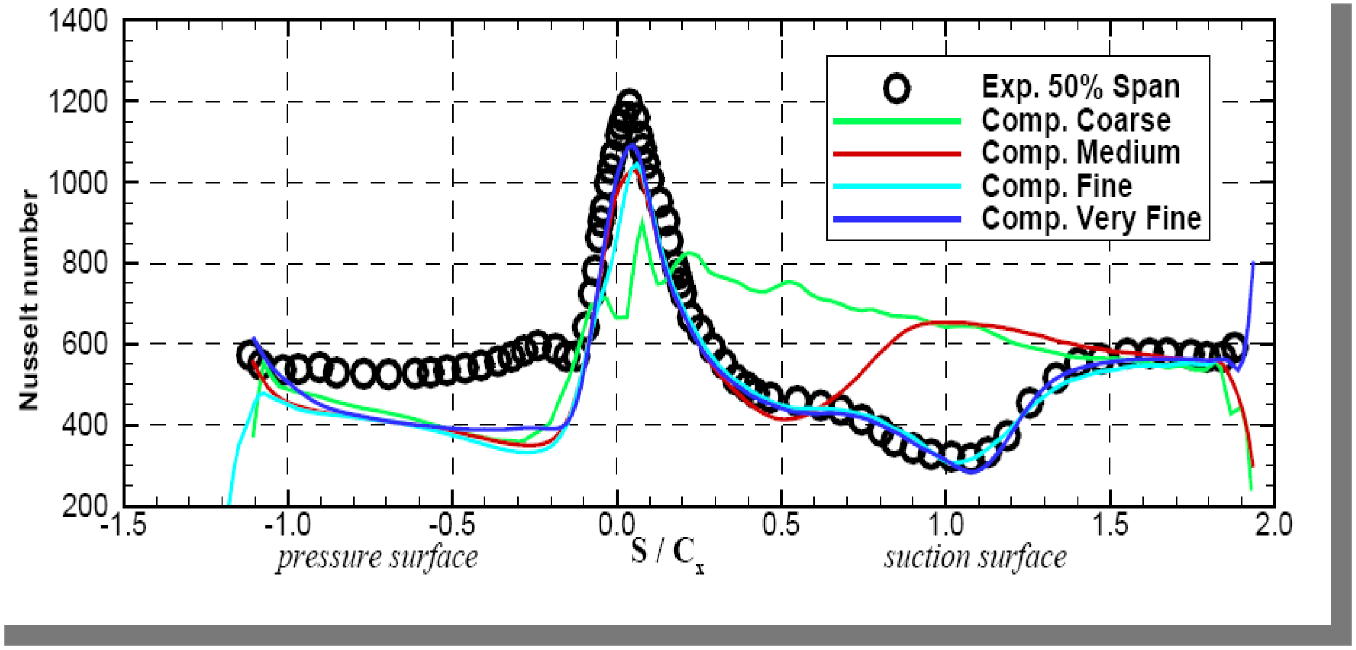


Figure: Courtesy of Ali Ameri, NASAGRC/OSU

Transition Modeling Conclusions

- **RANS-based models only applicable for bypass transition situations.**
- **Free-flight transition is normally modal growth – a reliable RANS-based method is not likely promising.**
- **LES is not promising either because accurately capturing the small disturbances is crucial – which LES will model/smear.**
- **Long Term Prospects – DNS, e^N methods.**

3D Boundary Layer Effects

- Mach 3.9 flow through a square duct
- Linear k-ω model unable to predict secondary flow
- EARS k-ω predicts anisotropy → secondary motions

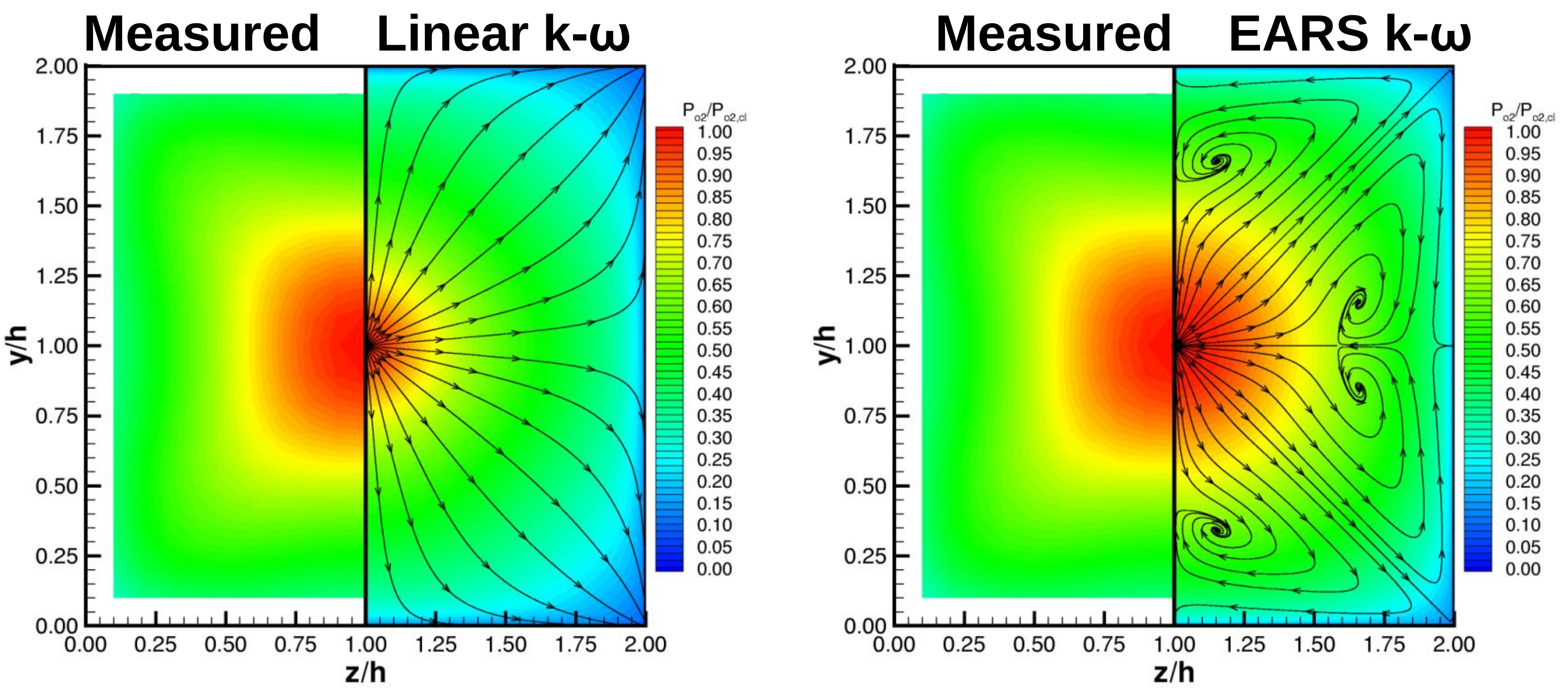
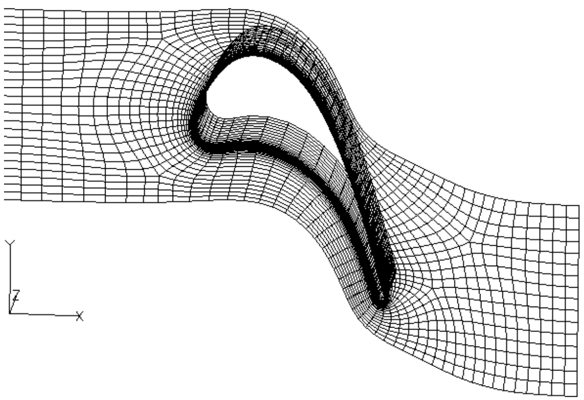


Figure: Courtesy of Rob Baurle, NASA LaRC

Turbine Blade Heat Transfer

- **Much finer grids required for heat transfer problems than aerodynamic cases where heat transfer is insignificant.**
- **v^2 – f model found to be superior to other RANS formulations.**



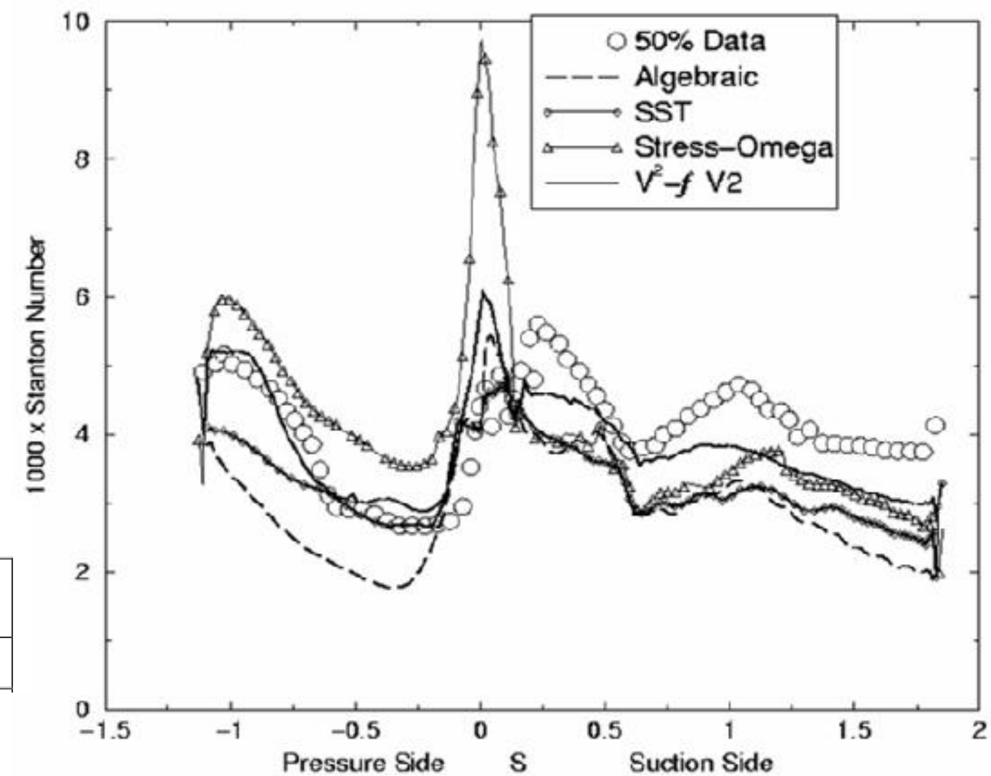


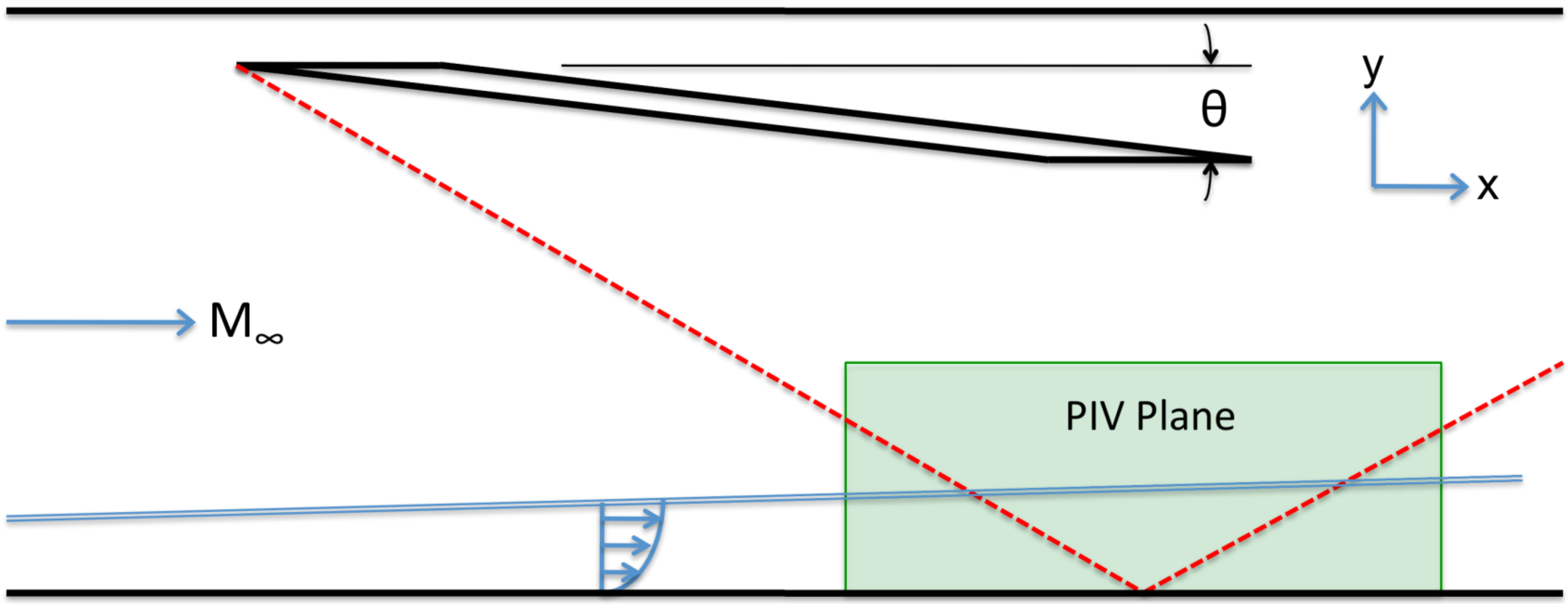
Table 1: Run Conditions

Case	Re_{in}	M_{ex}	Tu_{in}	Length scale	Inlet δ, % of half span
1	10^6	0.98	0.09	0.23	26

Figure: Courtesy of Ali Ameri, NASAGRC/OSU

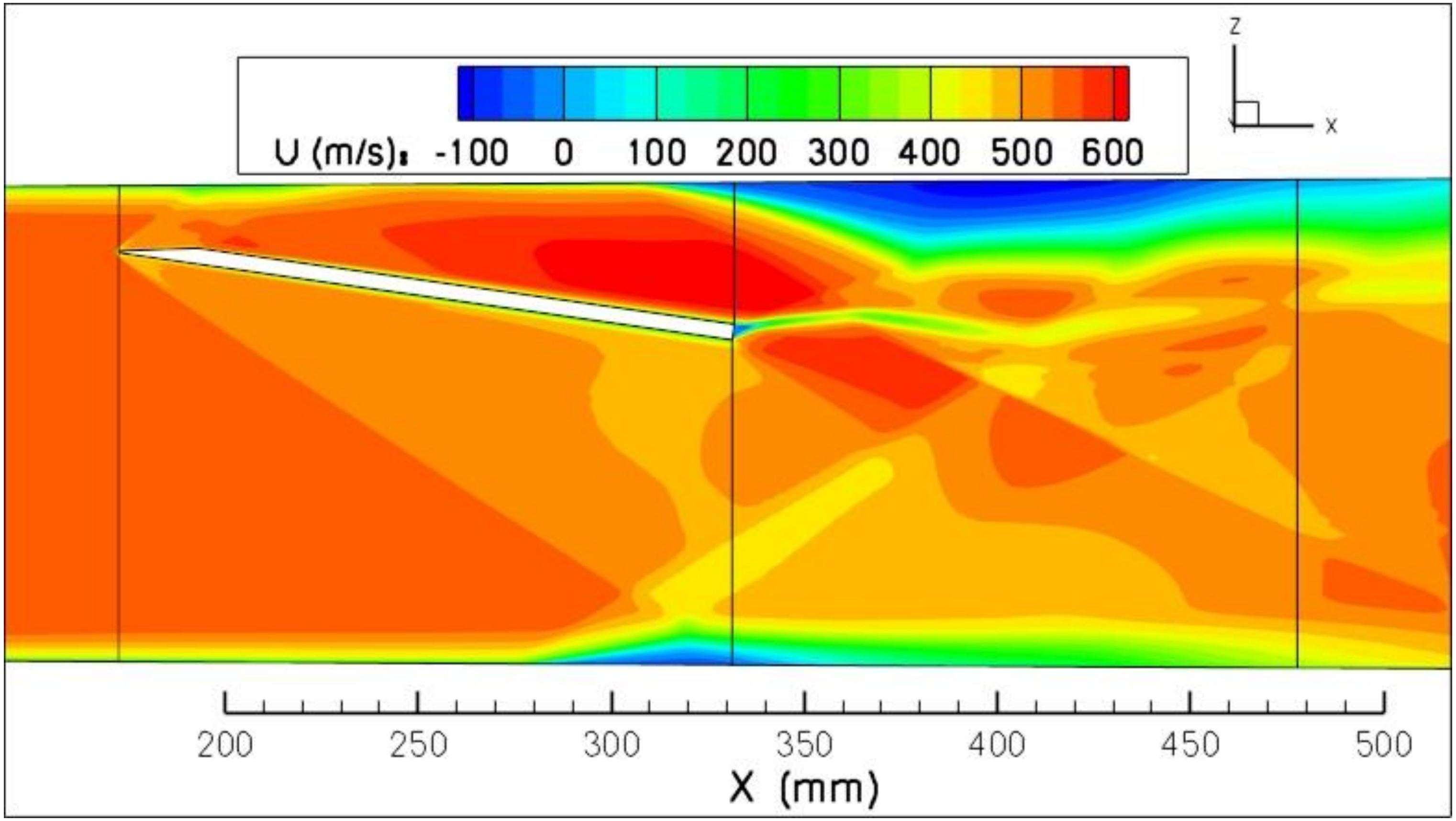
Shock-Wave Turbulent Boundary Layer Interactions (SWTBLIs)

- Pervasive to the entire hypersonic propulsion flowpath.
- Major challenge to RANS, LES and hybrid RANS-LES techniques.
- Nominally 2D problems are inherently 3D.



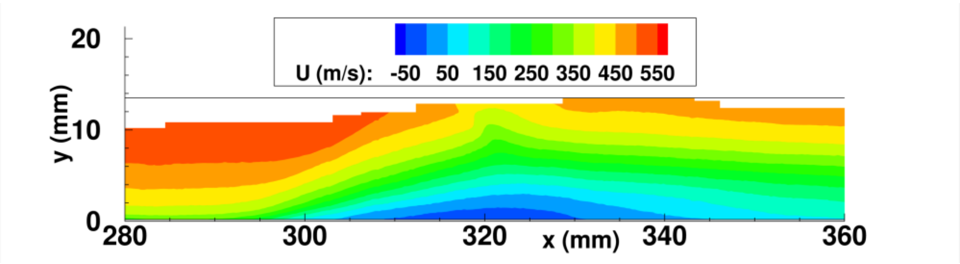
UFAST – Mach 2.25 Test Case

- **2010 AIAA Workshop: UFAST and U. of Michigan cases, targeted at representing supersonic aircraft inlets.**
- **Several organizations submitted results – RANS, LES, hybrids**

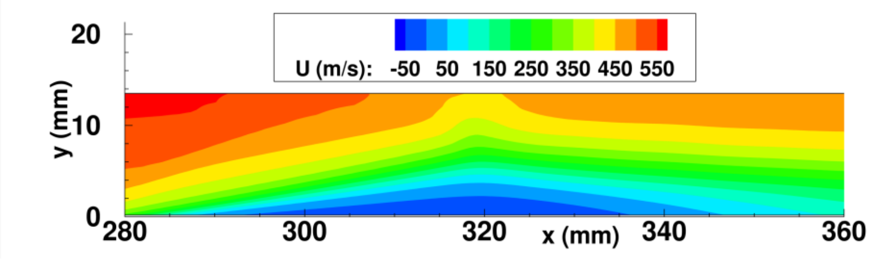


U Velocity Contours

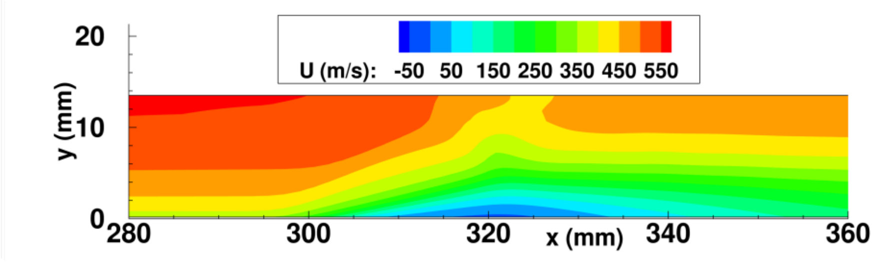
Experiment:



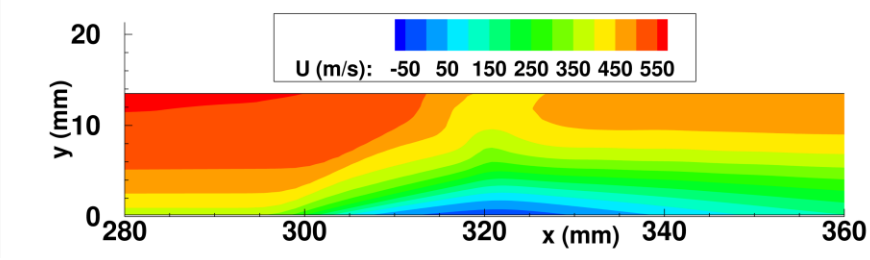
SST:



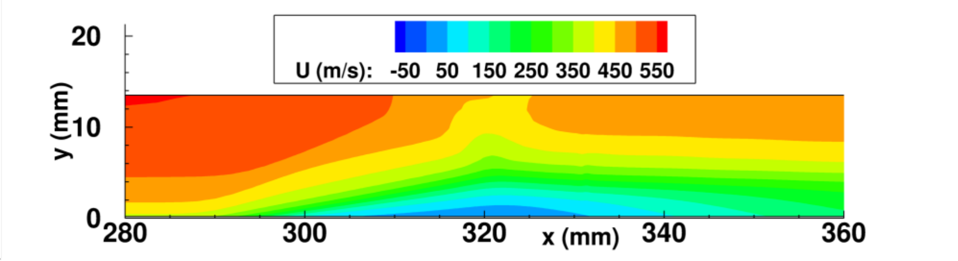
BSL:



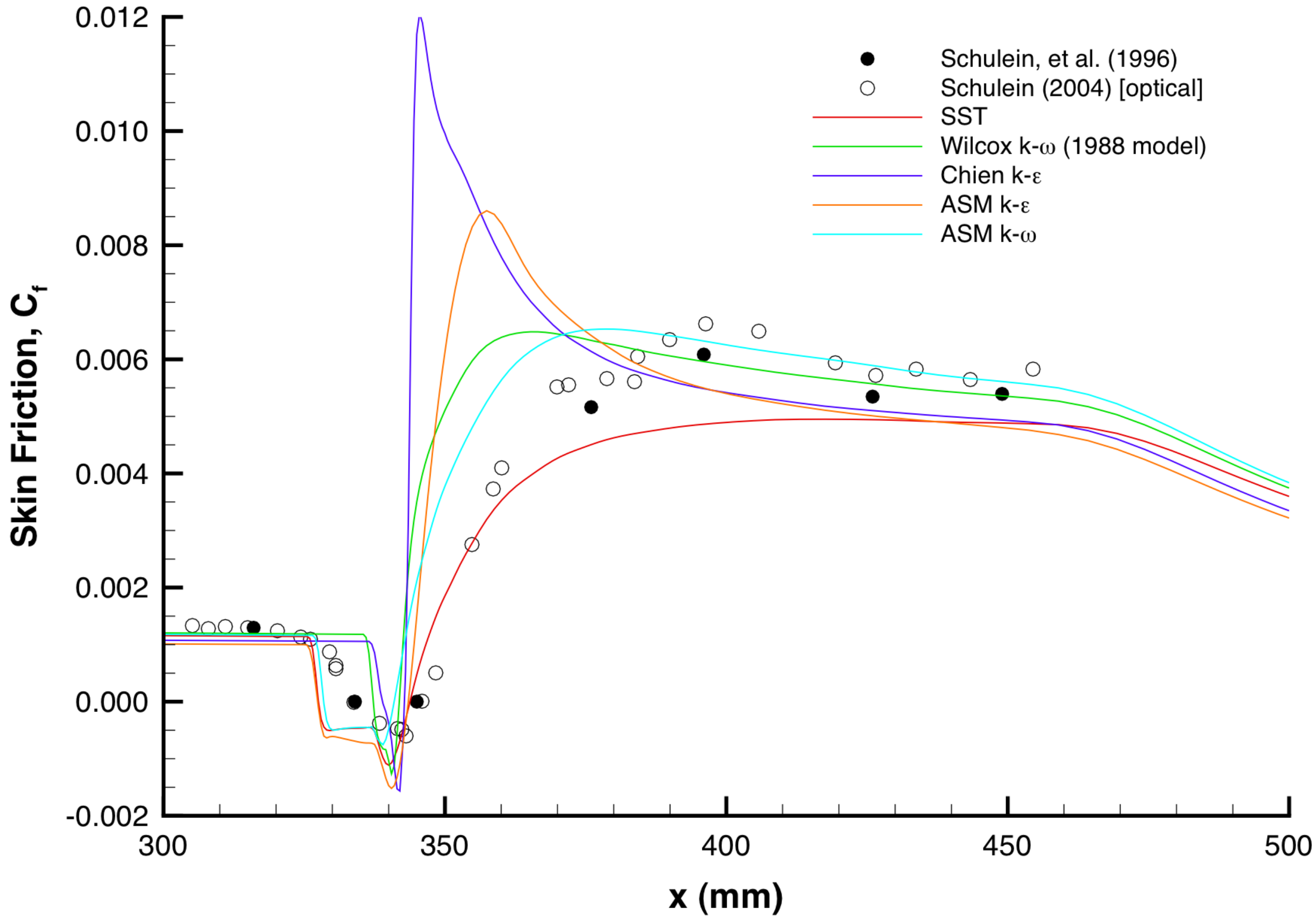
SA:



k-ω ASM:



Mach 5 SWTBLI



SWTBLI Modeling Conclusions

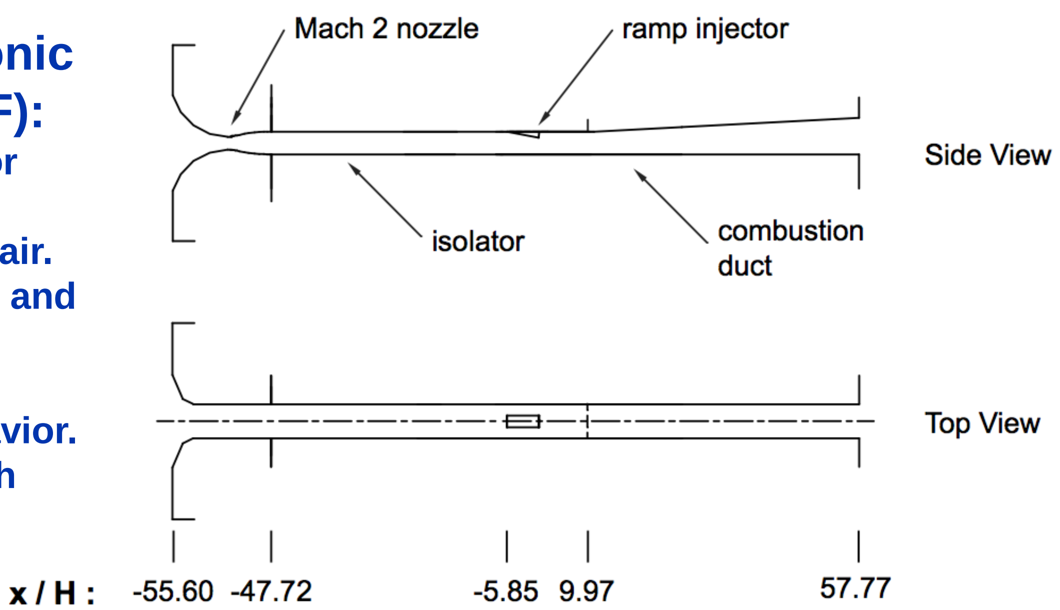
- k-ε models are generally overly optimistic on boundary layer health – smaller separations than expt.
- k-ω models usually work better for mild adverse pressure gradients, small separations, Menter SST predicts larger separations than expt.
- One equation models (i.e. SA) provide similar accuracy to multi-equation models.
- EASMs offer minimal improvement.
- Some success using LES at AIAA Workshop, inflow conditions & matching Re are significant challenges.
- Hybrid RANS-LES also being investigated – however, where is the switch from RANS to LES done?

Combustor/Exhaust System Modeling

- Several interacting phenomena – kinetics, turbulence, heat transfer, thermal-structural effects.
- Practical state-of-the-art: Arrhenius form for reaction rates, 2 eqn turbulence model, constant Pr_t, Sc_t. Specified wall temperatures or heat fluxes.
- Most practical scramjet experiments: only centerline pressures available; More data and/or unit problems are desirable.

University of Virginia Supersonic Combustion Facility (UVA SCF):

- Mach 5 enthalpy, Mach 2 isolator
- overall pressure ratio ~ 4
- H_2 fueled, clean air and vitiated air.
- Documented heat transfer rates and wall temperatures.
- NASA-sponsored experiments focused on mode transition behavior.
- Continuing experiments through National Center.



Turbulent transport in energy and species equations

Turbulent heat flux: $q_i^T = -\overline{\rho u_i' h} = -k^T \dfrac{\partial \hat{T}}{\partial x_i}$

Turbulent Prandtl number: $\mathrm{Pr}^T = \dfrac{\mu^T C_P}{k^T}$

Turbulent species flux: $m_i^T = -\overline{\rho u_i' w_1} = -D_{12}{}^T \dfrac{\partial \hat{w}}{\partial x_i}$

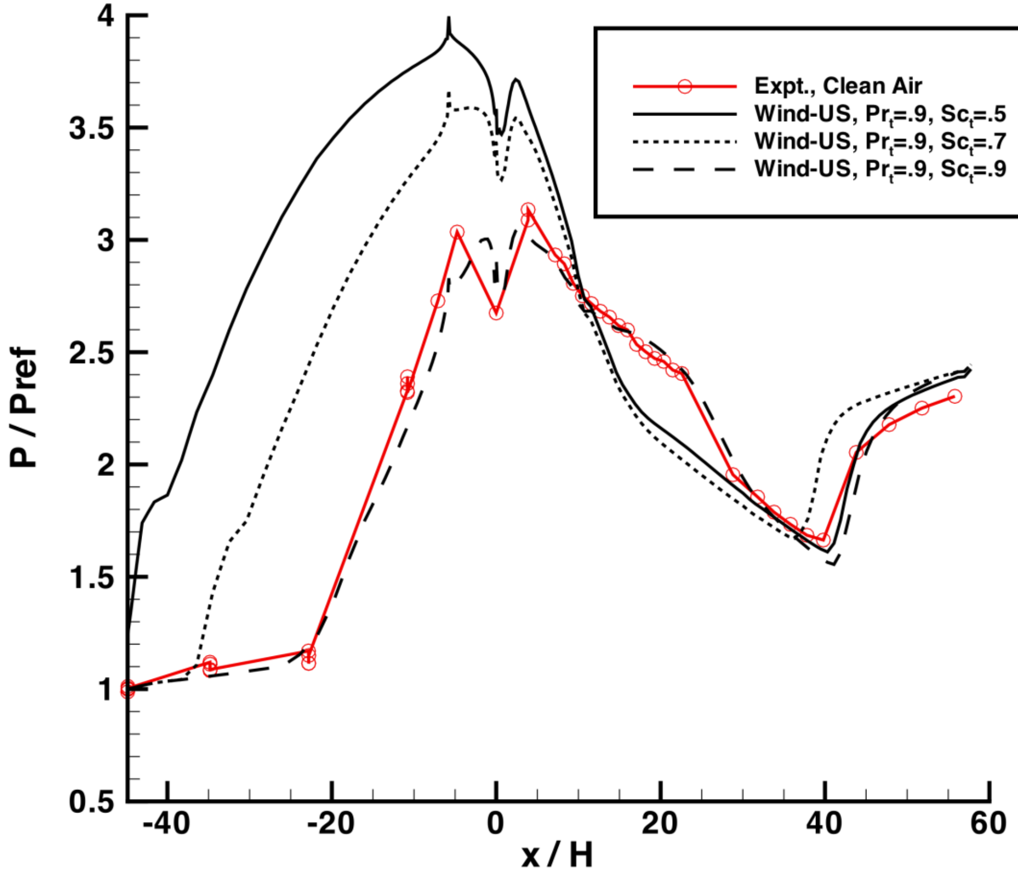
Turbulent Schmidt number: $Sc^T = \dfrac{\mu^T}{D^T}$

The turbulent Prandtl and Schmidt number are frequently set equal to 0.9. However, it is believed that realistic values can be significantly different for many flows – particularly in extreme environments such as scramjets.

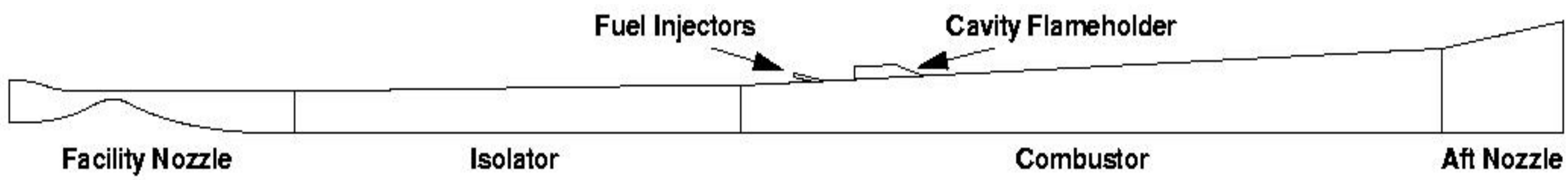
Sc_t Sensitivity for UVA SCF

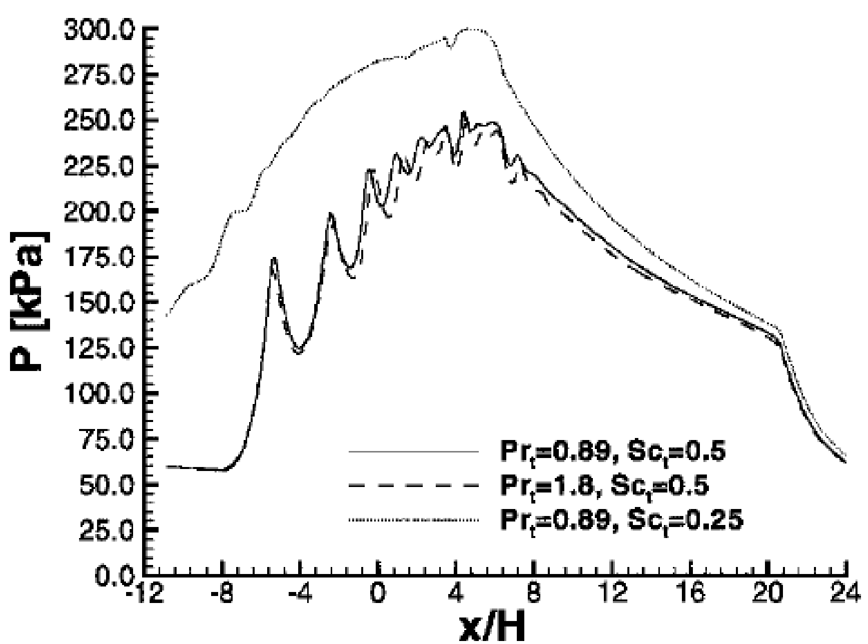
ϕ= 0.26, Clean Air

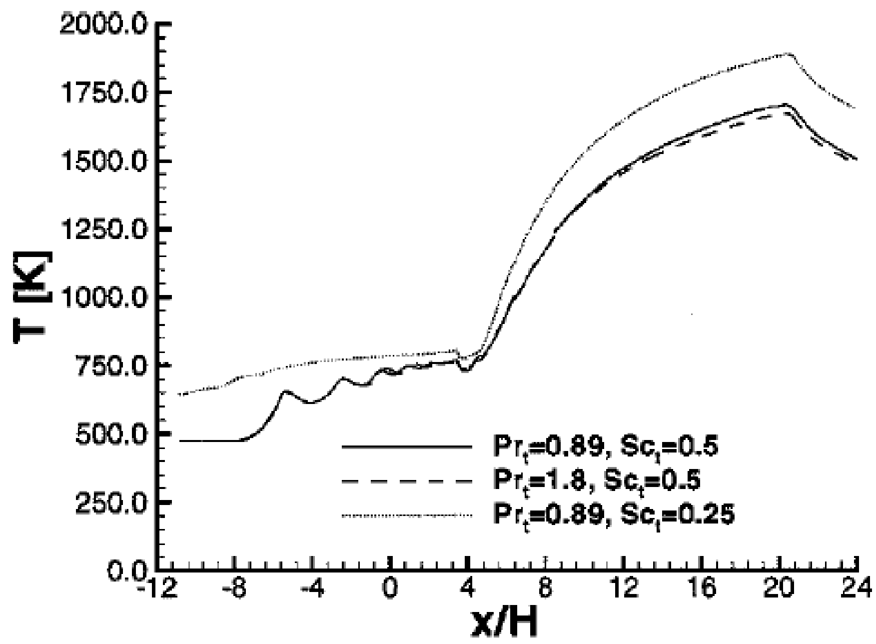
x/H = -45	Beginning of isolator
x/H = 0	Fuel exit/ ramp base
x/H = 57	Nozzle exit to ambient



Pr_t and Sc_t Sensitivity for USAF Scramjet



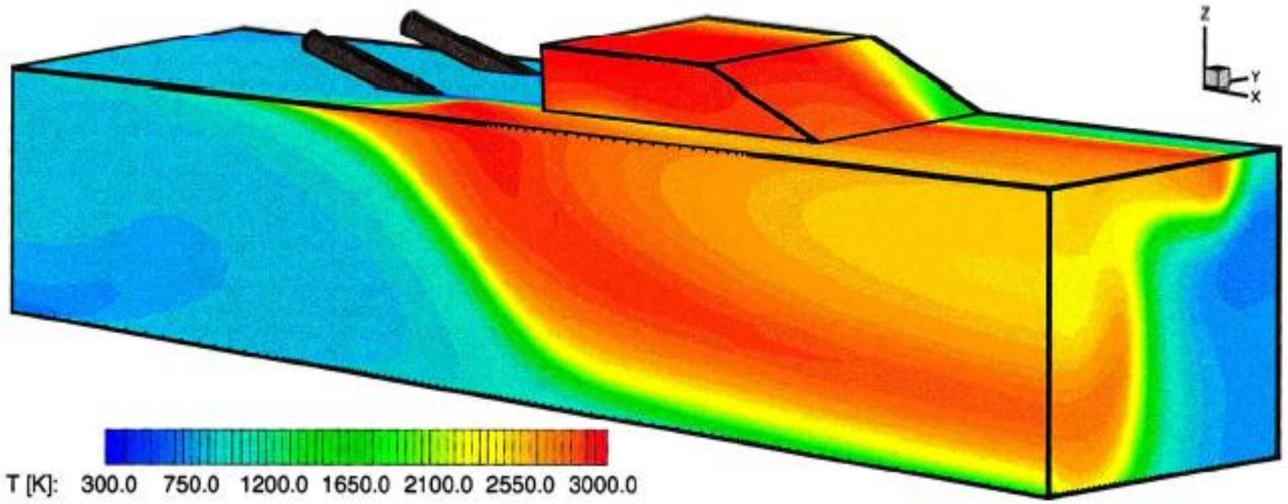




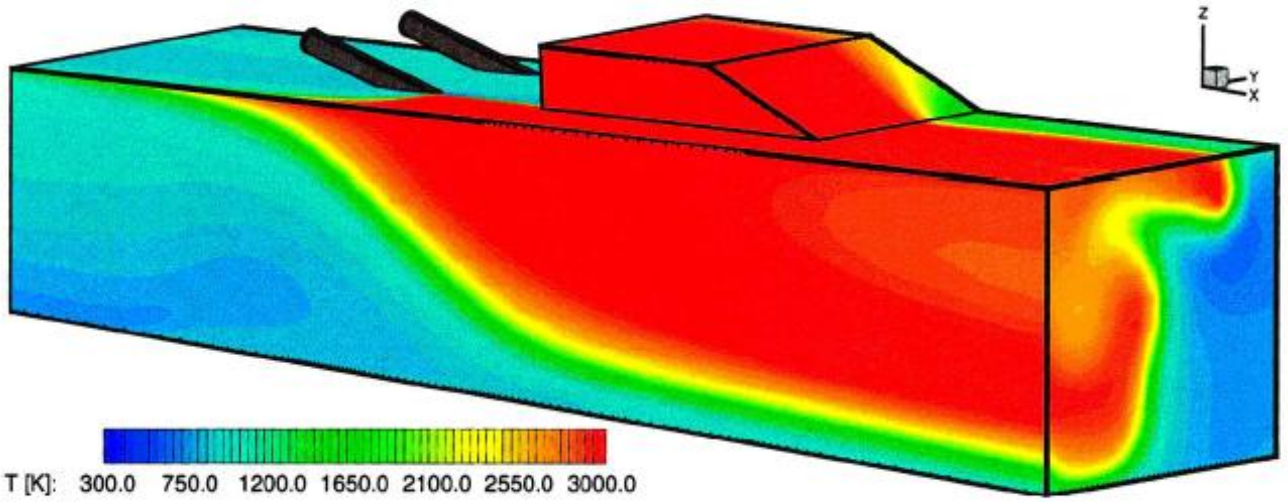
An "optimized" Pr_t and Sc_t for one case do not guarantee optimal performance for other ϕ's, turb. models, kinetics, etc.

Figure: Courtesy of Robert A. Baurle, NASA LaRC

Pr_t Sensitivity for USAF Scramjet



$Pr_t = 0.89$

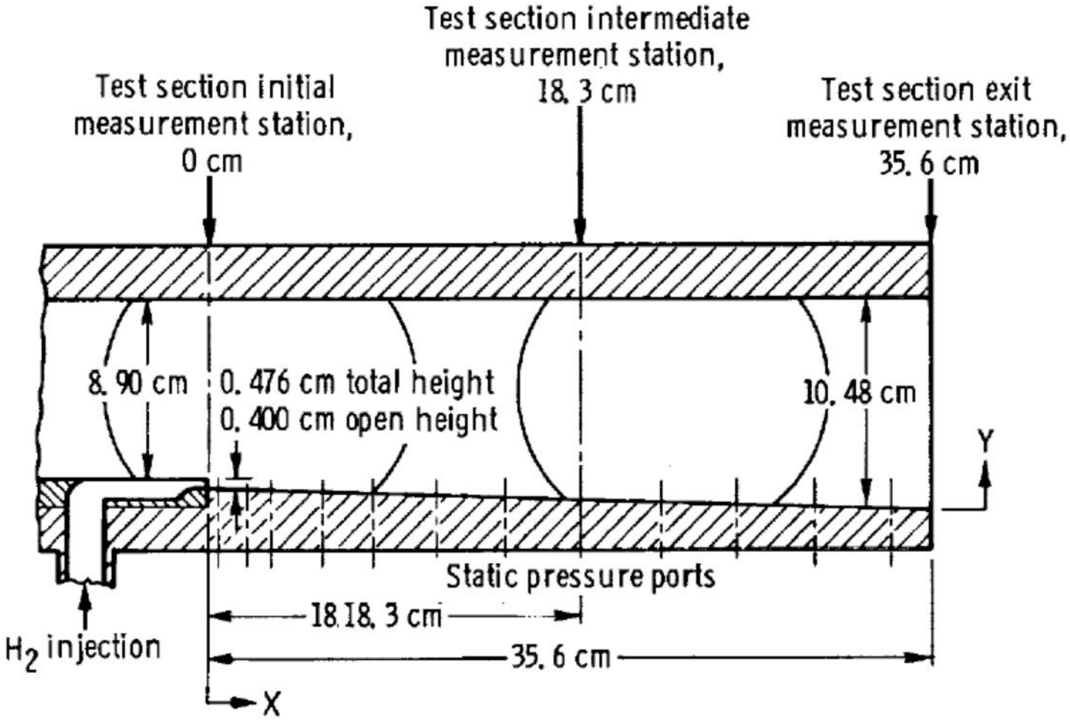


$Pr_t = 1.8$

Figure: Courtesy of Robert A. Baurle, NASA LaRC

Burrows-Kurkov "Unit" Test Case

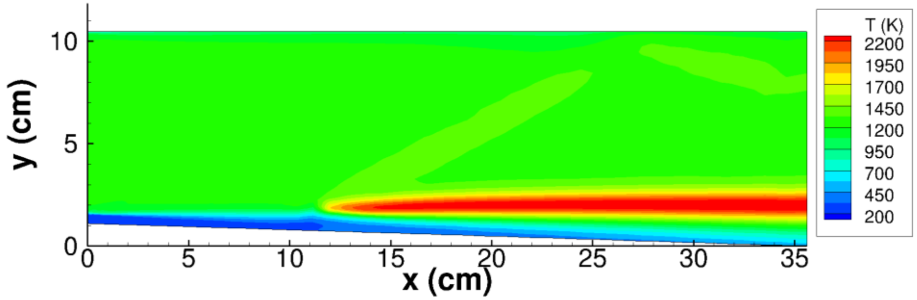
- Mach 2.4 vitiated air / sonic hydrogen experiment (1973).
- Used extensively for investigations/validation of H_2-air CFD methods (kinetics, variable Pr_t , Sc_t , hybrid RANS-LES...), perhaps overused.
- Measurements of species concentrations and temperatures.



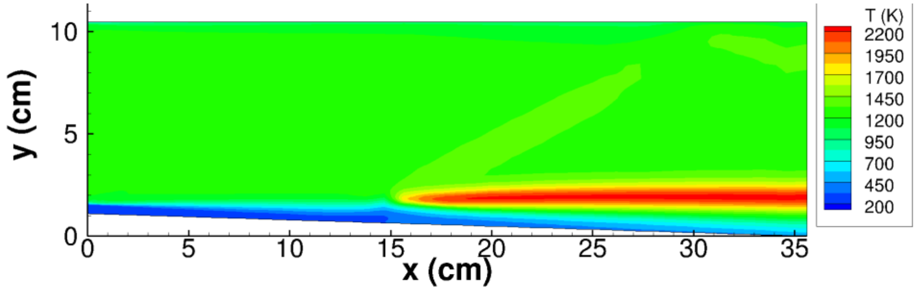
Sc_t Effects on Ignition Point for Burrow-Kurkov Test Case

Pr_t = 0.7 (constant) for all cases

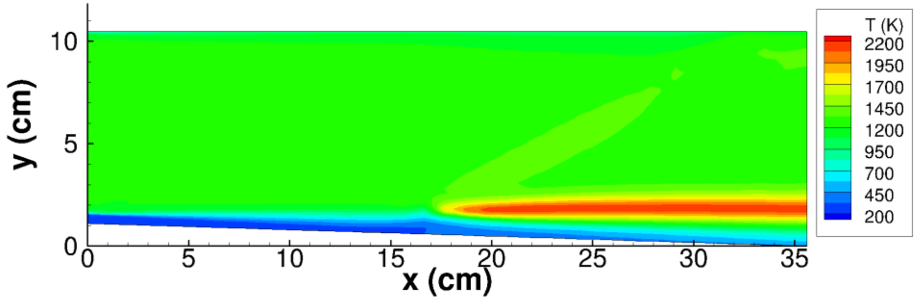
Sc_t = 0.5



Sc_t = 0.7

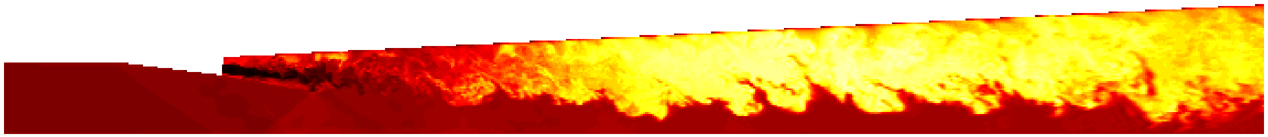


Sc_t = 0.9



Hybrid RANS/LES Calculations of UVA Dual-Mode Scramjet, $\Phi = 0.17$

Temperature



Eddy viscosity

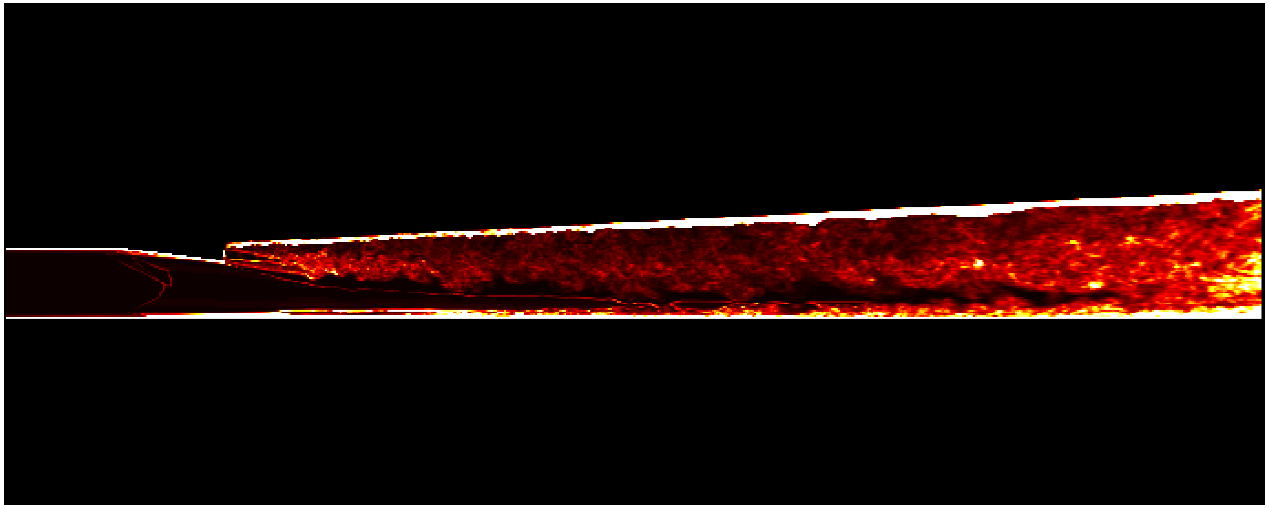


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Figure: Courtesy of Jack Edwards, NCSU

Hybrid RANS/LES Calculations of UVA Dual-Mode Scramjet, Φ = 0.17

CARS comparisons (temperature): (X/H = 6, 12, 18)

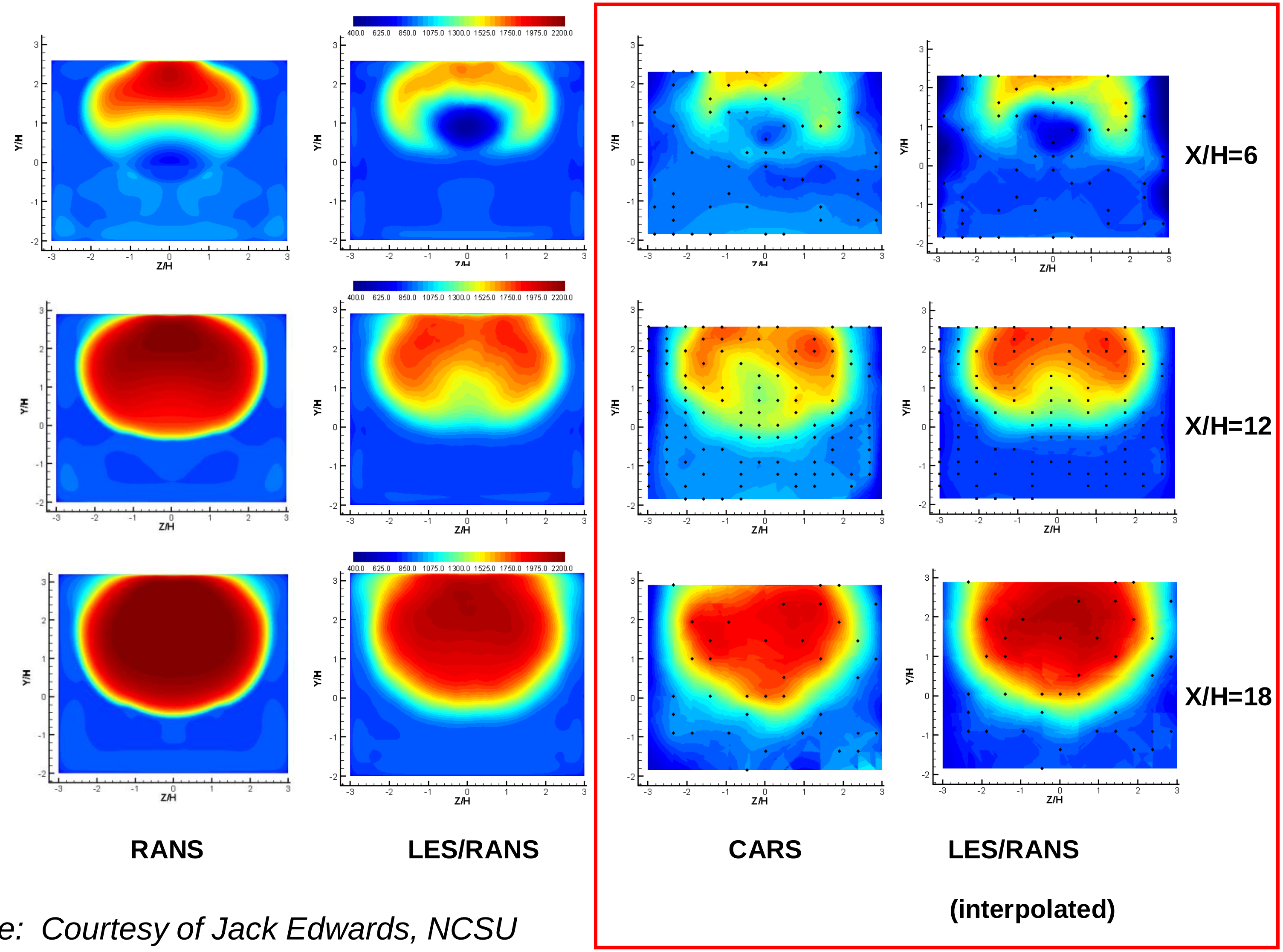


Figure: Courtesy of Jack Edwards, NCSU

Combustor Modeling R&D at NASA GRC

- High-fidelity prediction of liquid combustion in practical engineering devices remains elusive despite significant advances in combustion modeling and simulation over the past decade.
- Current major pacing items include modeling of turbulence-chemistry interactions, and modeling of liquid fuel atomization and evaporation.
- LES-based efforts of varying fidelity have been under development such as:
  - Filtered Density Function Approach (FDF) – Givi,Jaberi, Madnia (NCHCCP)
  - Linear Eddy Model - Menon
- GRC is developing the time-filtered Navier-Stokes (TFNS) approach, which, unlike the traditional LES approach, allows the attainment of a grid-independent solution.
- To account for the effects of turbulent fluctuations on the chemical reaction source terms, stochastic sub-grid models are invoked when modeling the filtered reaction source terms.
- Two different sub-grid models have been developed: eupdf-like and lem-like, and they are currently being assessed.

Figure: Courtesy of Nan –Suey Liu, NASA GRC

Emulating Turbulence-Chemistry Interactions

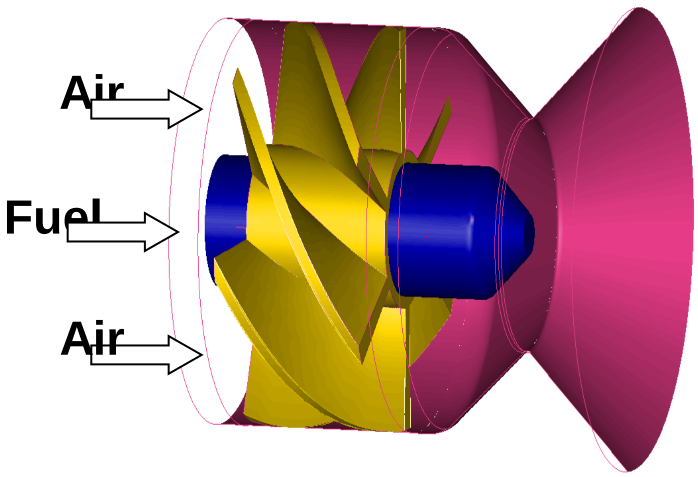
- **Unmixed model (umx):** Effects of turbulent fluctuations on chemical reaction source terms are ignored.

- **Eulerian Probability Density Function model (eupdf-like):** Effects of turbulent fluctuations on chemical reaction source terms are accounted for by a stochastic sub-grid model having features of the traditional EUPDF previously used in RANS.

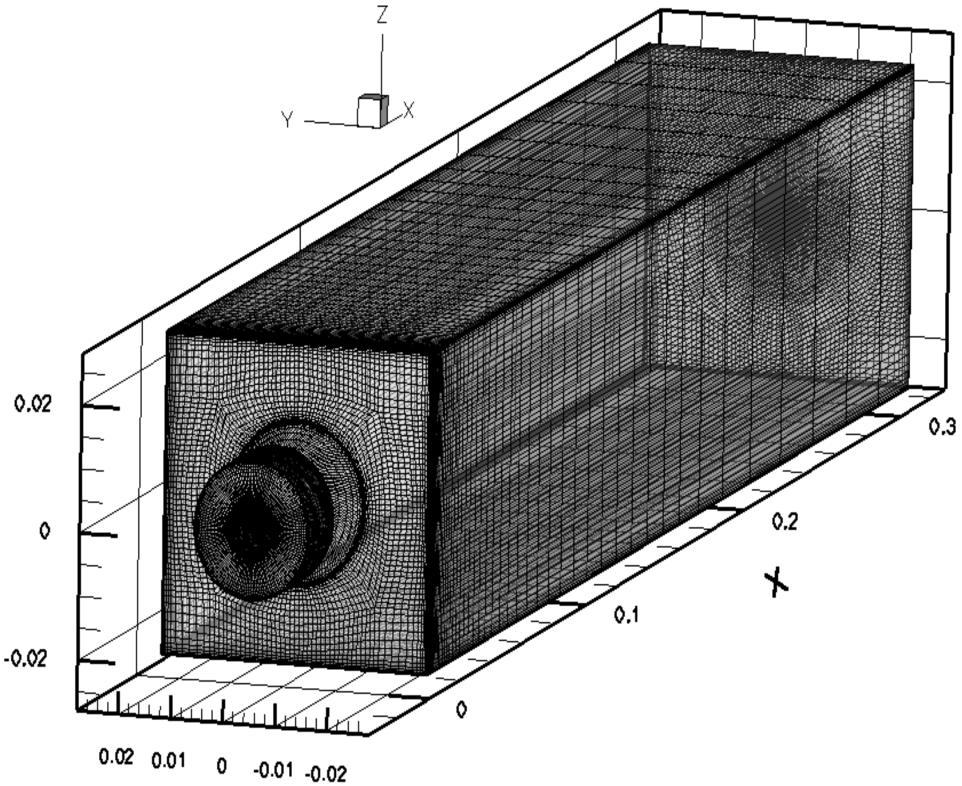
- **Linear Eddy Mixing model (lem-like):** Effects of turbulent fluctuations on chemical reaction source terms are accounted for by a stochastic sub-grid model having features of the traditional LEM previously used in LES.

Figure: Courtesy of Nan –Suey Liu, NASA GRC

Single-Element Lean Direct Injection (LDI) Combustor



Geometry of the Single Element



Grid Distribution for the LDI Combustor (861823 hexahedral elements)

Figure: Courtesy of Nan –Suey Liu, NASA GRC

Preliminary Comparison Between umx, eupdf-like, and LEM-like Models

TFNS of liquid combustion in a single-element LDI configuration:

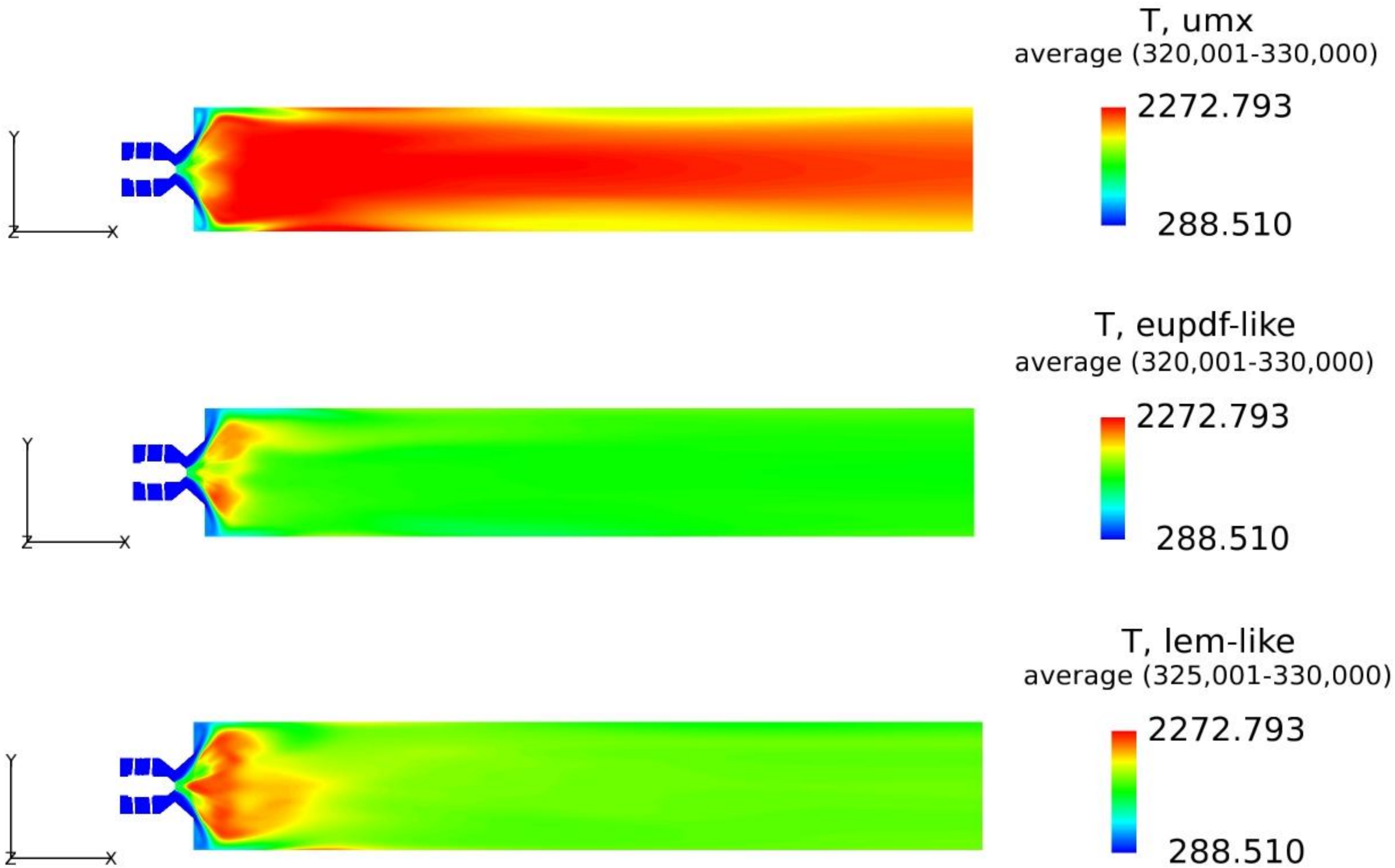


Figure: Courtesy of Nan –Suey Liu, NASA GRC

Compressible Mixing

- Most recent free shear layer mixing research has been in support of jet aeroacoustics research (subsonics and supersonics).
- Practical state-of-the-art for RANS is also two-equation modeling.
- Some research in variable Pr_t for hot jet cases.

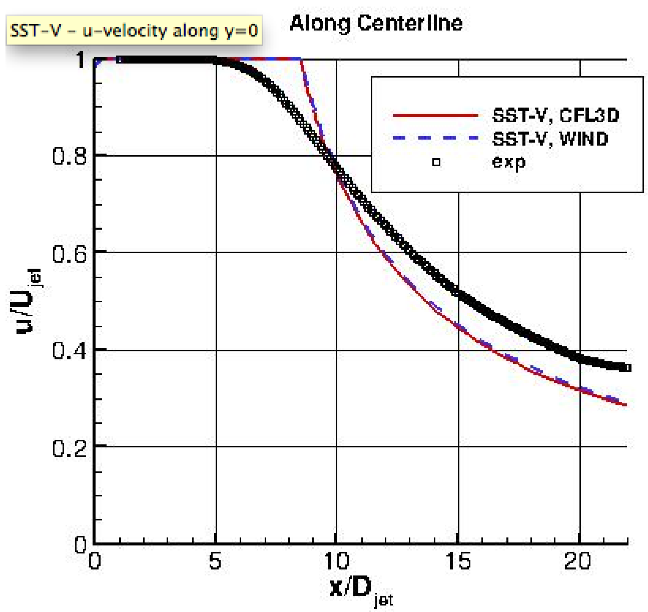
- Most research support is towards LES-based methods.
- Key LES issues:
  1. Inflow boundary treatment
  2. Grid resolution/sensitivity
  3. Farfield noise propagation techniques.

Jets and Mixing - RANS

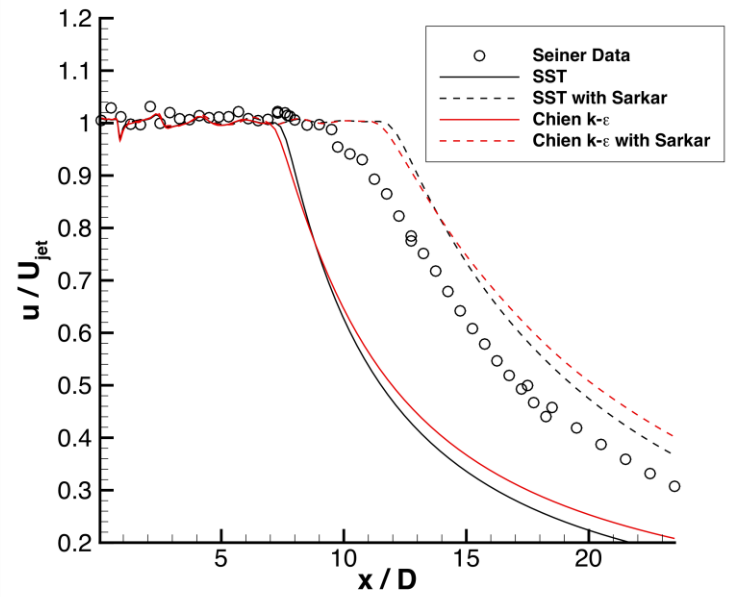
RANS Findings:

- RANS **underpredict** mixing for incompressible jets – initial shear layer is difficulty.
- Uncorrected RANS models **overpredict** mixing rate for supersonic jets and mixing layers.
- Effects of temperature and 3D jet effects are not modeled correctly.
- Compressibility corrections (i.e. Sarkar) are highly empirical and do not reproduce correct fluid dynamic effects.

Mach 0.5 Jet



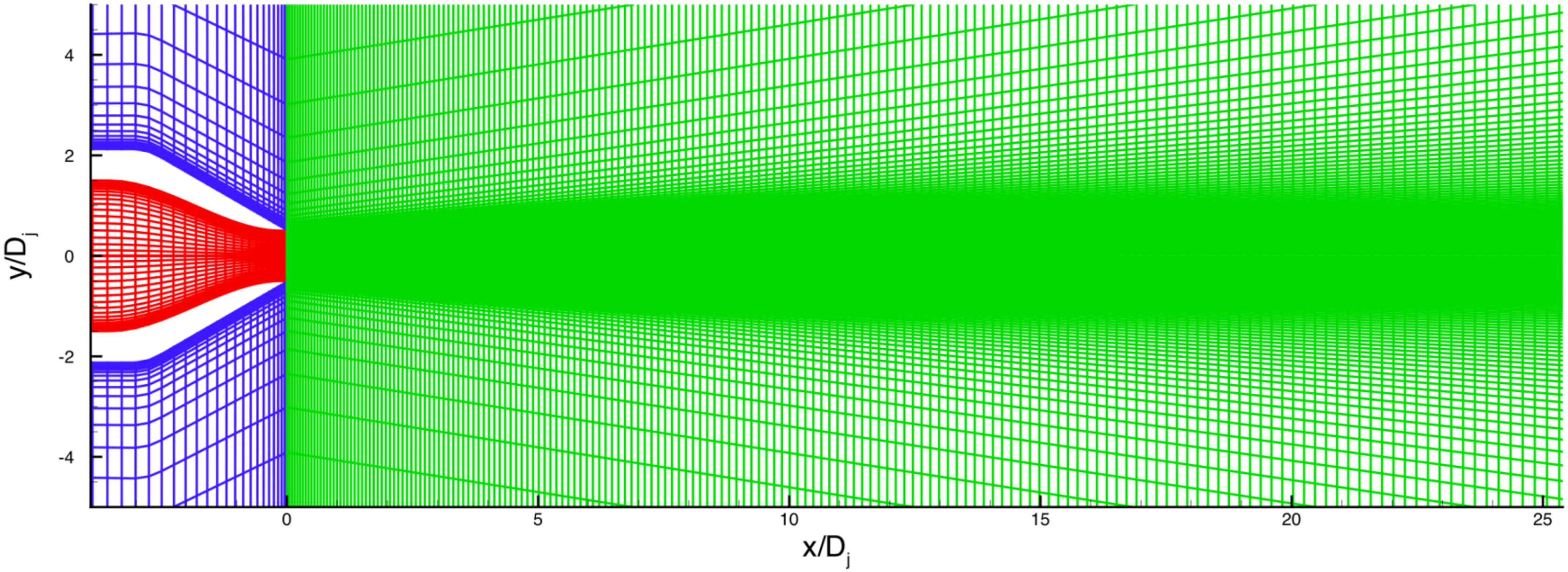
Mach 2.0 Jet



Jet Mixing - LES

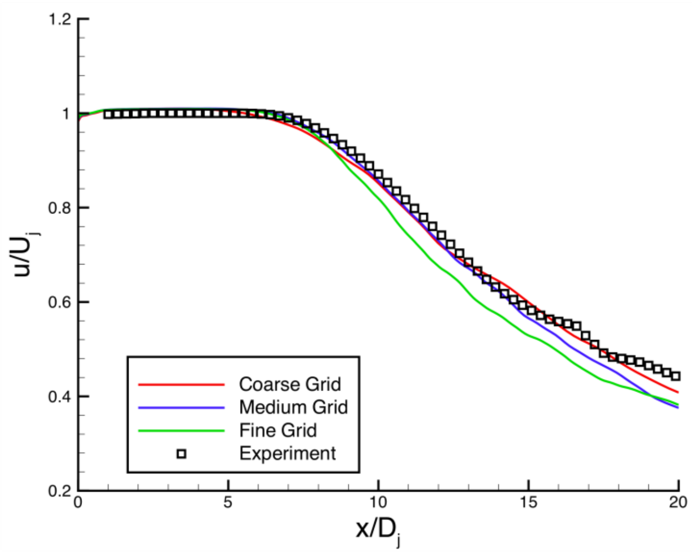
• **Acoustic Reference Nozzle (ARN) and Simple Metal Chevron (SMC) configurations – tested at GRC, investigated by several LES researchers.**
• Two Mach 0.9 jet simulations considered here: (1) DeBonis (GRC) DRP with 4 stage RK, 3.5 - 9.2 million points and (2) Uzun (FSU), 4th order compact scheme with 4 stage RK, 50 - 400 million points.

DeBonis (GRC) grid:

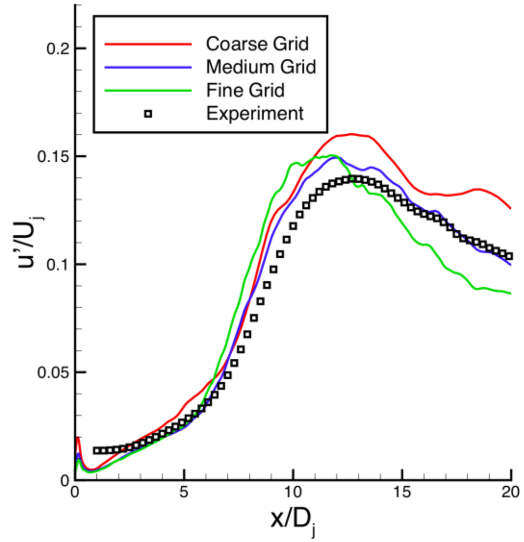


ARN - Centerline Statistics (GRC)

Mean Axial Velocity



Axial Turbulent Intensity



Radial Turbulent Intensity

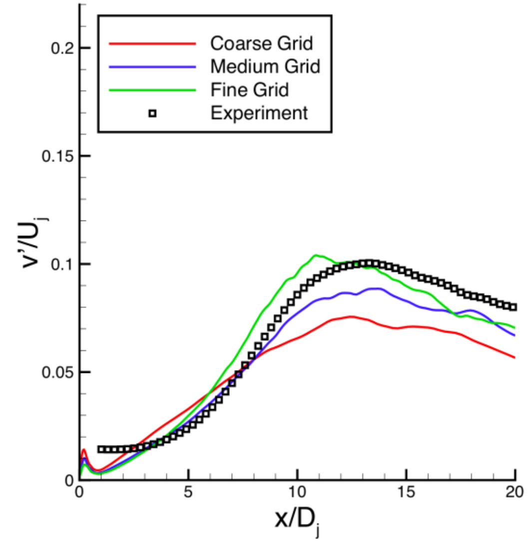
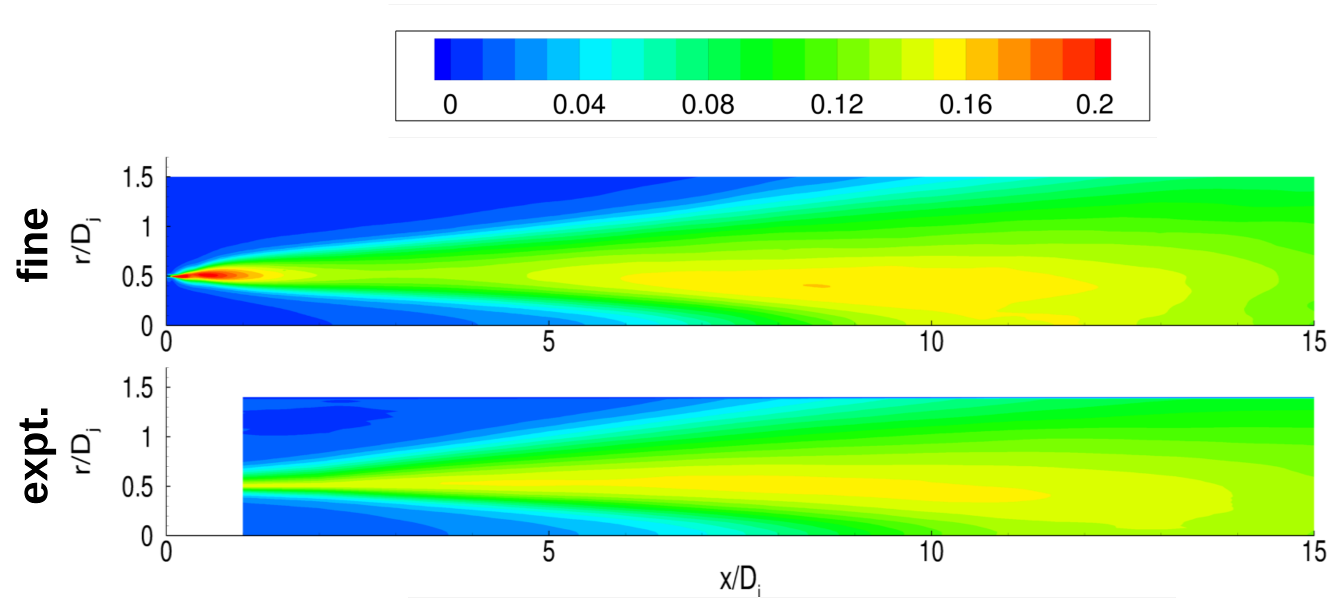


Figure: Courtesy of Jim DeBonis, NASA GRC

Turbulence Intensity Comparisons

Axial Turbulent Intensity



Radial Turbulent Intensity

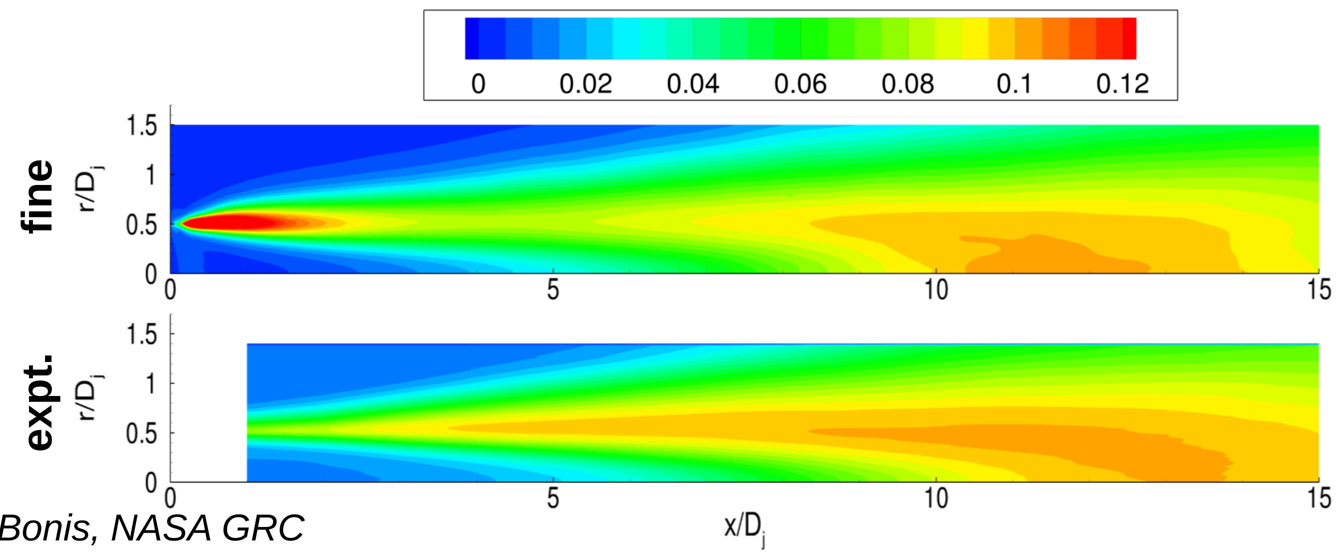


Figure: Courtesy of Jim DeBonis, NASA GRC

SMC – Jet Decay and Acoustic Radiation

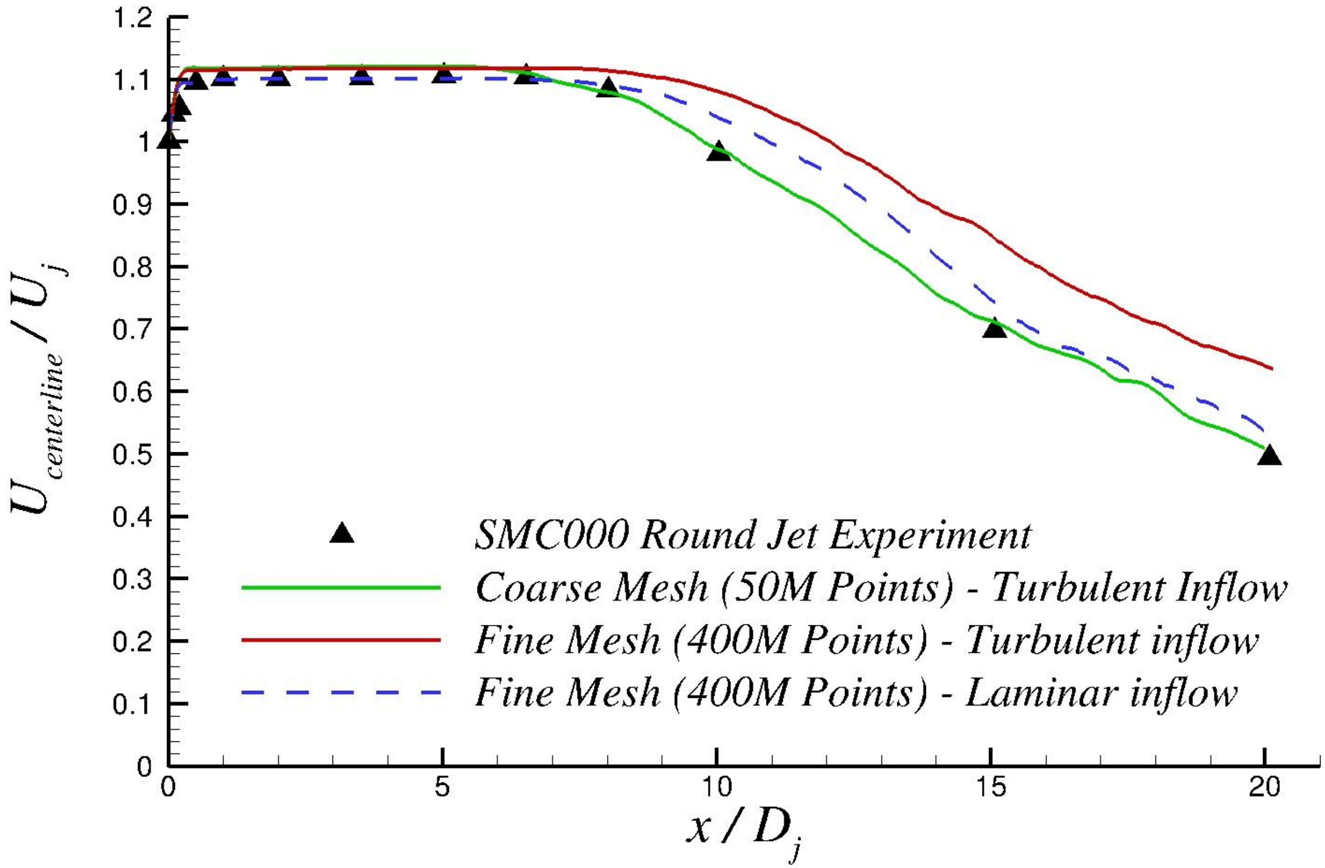


Figure: Courtesy of Ali Uzun, FSU

SMC – Jet Decay and Acoustic Radiation

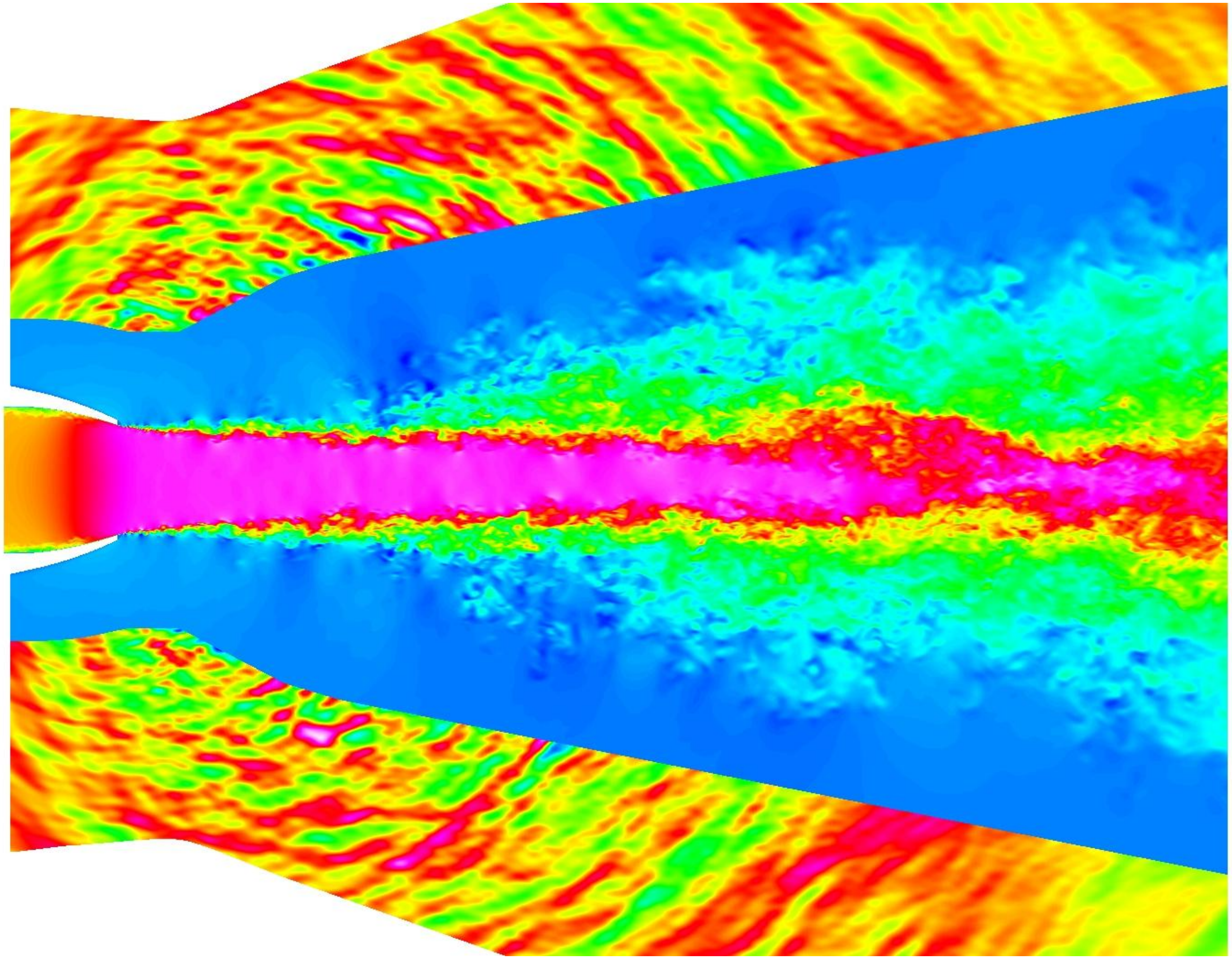


Figure: Courtesy of Ali Uzun, FSU

Combustor/Exhaust System Modeling Enhancement Needs

- **RANS:**
  - Better prediction of 3D, compressible mixing; highly separated/recirculating flow in flameholder/cavity, SWTBLIs, turbulent-chemistry interactions.
  - More accurate boundary conditions for thermal state.
  - Variable Pr_t and Sc_t capability.
- **LES:**
  - Capability to handle wall bounded and free shear layer regions. Hybrid RANS/LES methods are under investigation – but location of RANS-to-LES switch has significant effect.
  - Significant uncertainty remains in how to best perform jet/mixing simulations. Highly desirable to establish “best practices” if possible.
  - Models for turbulent/chemistry interactions, i.e. Filtered Density Functions (FDFs).

Experimental – Validation Data Needs

- Centerline pressure distributions are not sufficient for validation / calibration of turbulent flow CFD. There are too many interacting features in scramjet flowpaths – unlike subsonic/transonic aerodynamics.
- More complete turbulent statistics for momentum, thermal, and species transport are needed.
- Advanced Diagnostics: CARS, PLIF, PIV – for unit problems, then more complex cases.
- Quantify uncertainty – e.g. PIV is powerful technique, but prone to high uncertainty in crucial regions such as initial mixing regions.
- Consider revisiting experiments such as Burrows-Kurkov with the advanced techniques.
- Design experiments to avoid contamination of focus region – i.e. SWBLI cases – nearly all experiments are in small tunnels where sidewall separations dominate region of interest.

Conclusions

- **Many extremely difficult challenges remain in turbulence modeling for air-breathing propulsion flows.**
- **Status of RANS Modeling for high speed propulsion flowpaths: Not much advancement in practical state-of-the-art in 2 decades.**
- **Dominant features of 3-D flow, large separations, SWTBLIs, chemically reacting flow, compressibility, turbulent transport of heat and species – overwhelm the capabilities of current RANS methods.**
- **Tweaking one turbulence modeling parameter while holding all others fixed until centerline pressure distribution matches experimental data (typical practice for scramjets) is of minimal value.**
- **LES and related methods are demonstrating some promise, but have their own modeling issues and (1) are not of sufficient maturity for most problems, (2) computing power is not readily available to use in a production engineering environment, (3) minimal consistency between groups in how to achieve most accurate results.**