Simulation and Modeling of Hypersonic Turbulent Boundary Layers Subject to Pressure Gradient and Wall Cooling (Year 1)

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Funded by ONR (Award No.: N00014-19-1-2501, N00014-20-1-2194), and monitored by Dr. Eric Marineau

2020 AFOSR/ONR/HVSI Hypersonic Aerothermodynamics Portfolios Review, July 29, 2020

Background

- Challenges in studying hypersonic turbulence
  - Limited experimental data
    - Flight measurements: expensive and limited scope
    - Wind-tunnel experiments: mismatch in flow conditions relative to flight
    - In general: lack of resolution in global measurements (especially in the vicinity of the wall)
  - *Ad hoc* turbulence models and model parameters

- DNS of supersonic and hypersonic turbulent flows
  - Go where experiments cannot
  - Understand flow physics
  - Improve predictive capabilities
  - Assess/develop flow-control techniques

- Lack of benchmark DNS datasets in the **high-Mach-number, cold-wall** regime
  - Existing DNS largely focused on moderately supersonic flows ($M < 5$) with adiabatic walls

Background

- **Specific objectives of the present project:**
  - ☐ Development of DNS database of hypersonic turbulent boundary layers subject to **pressure gradient** and **wall cooling**
    - Canonical geometries
      - 2-D planar convex and concave walls
      - 2-D circular ogive
      - 3-D elliptic ogive
    - Adiabatic wall ($T_w/T_r = 1$) and cold wall ($T_w/T_r << 1$)
    - One-to-one comparison against experiments at Texas A&M U. (Prof. R. Bowersox's group)
  - ☐ Physical characterization of boundary-layer turbulence
    - Budgets of TKE and Reynolds-stress transport
    - Compressibility transformations
  - ☐ Assessment of turbulence models
    - Reynolds-stress transport (RST) models
    - Turbulent heat flux model by Bowersox

- **Benefits to DoD:** Support DoD's efforts of developing advanced turbulence models for improving computational simulations of hypersonic vehicles

Previous Work

- **DNS datasets of supersonic and hypersonic TBLs** (*Zhang et al. Vol. 56, No. 11, pp. 4297-4311, AIAAJ, 2018*) – developed in the context of acoustic radiation from TBLs
  - ☐ Spatially developing, zero-pressure gradient, flat plate
  - ☐ Covers a wide range of freestream Mach numbers (M_∞ = 2.5 - 14) and wall-to-recovery temperature ratios (T_w/T_r = 0.18-1.0)

Case	M_∞	U_∞, m/s	ρ_∞, kg/m^3	T_∞, K	T_w, K	T_w/T_r	δ_i, mm
M2p5	2.50	823.6	0.100	270.0	568.0	1.0	4.0
M6Tw025	5.84	869.1	0.044	55.2	97.5	0.25	1.3
M6Tw076	5.86	870.4	0.043	55.0	300.0	0.76	13.8
M8Tw048	7.87	1155.1	0.026	51.8	298.0	0.48	20.0
M14Tw018	13.64	1882.2	0.017	47.4	300.0	0.18	18.8

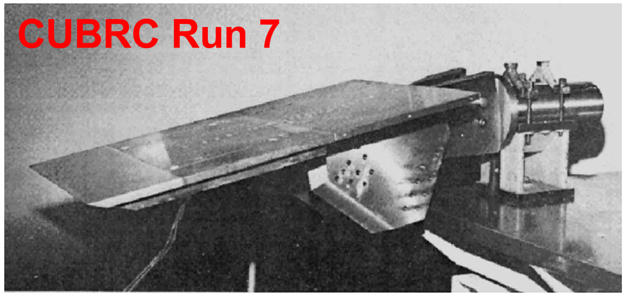
  - ☐ Friction Reynolds number (Re_τ) is kept within the narrow range of 450– 650

Case	x_a/δ_i	Re_θ	Re_τ	Re_{δ_2}	Re_τ^*	θ, mm	H	δ, mm	z, μm	u_τ, m/s	$-B_q$	M_τ
M2p5	53.0	2835	510	1657	1187	0.58	4.1	7.7	15.0	40.6	0	0.08
M6Tw025	88.6	2121	450	1135	932	0.20	8.4	3.6	8.0	33.8	0.14	0.17
M6Tw076	54.1	9455	453	1746	4130	0.95	13.6	23.8	52.6	45.1	0.02	0.13
M8Tw048	56.9	9714	480	1990	4092	1.19	17.4	35.2	73.5	54.3	0.06	0.15
M14Tw018	199.3	14408	646	2354	4925	1.35	37.6	66.1	102.4	67.6	0.19	0.19

Summary of New Results

- ➢ Conducted DNS of a zero-pressure-gradient (ZPG) TBL at $M_\infty = 11.1$ on a highly-cooled flat plate (representative of CUBRC Run 7)
  - ❑ Extended the existing DNS database to a moderately higher Reynolds number ($Re_\tau \cong 1200$)
  - ❑ Studied hypersonic turbulence with strong wall cooling ($T_w/T_r \cong 0.2$)
  - ❑ Assessed Bowersox's algebraic energy flux (AEF) model using DNS data

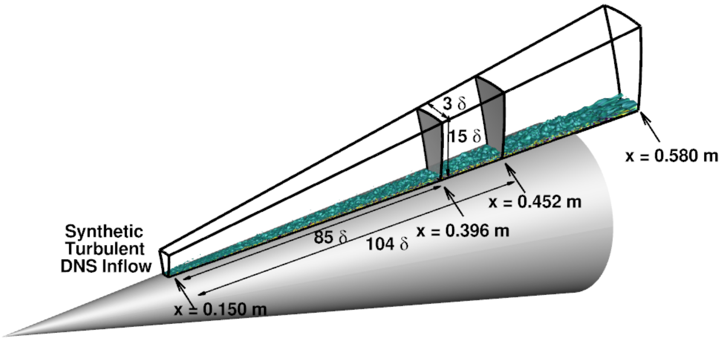
DNS of ZPG TBL over a highly-cooled flat plate



Gnoffo, JSR 2013

- ➢ Simulated a TBL at $M_\infty = 8$ on a 7-deg half-angle circular cone (representative of Sandia's experiment)
  - ❑ Established a procedure of conducting DNS for hypersonic TBLs over an axisymmetric hypersonic body
  - ❑ Laid a foundation for follow-on study of hypervelocity ogive cylinder of interest to ONR

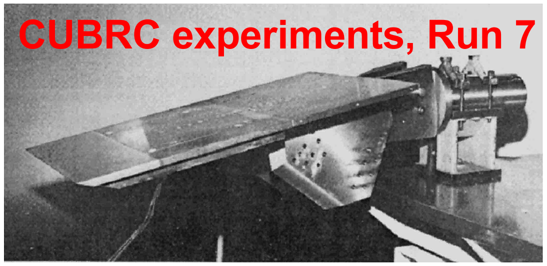
DNS of a Mach 8 TBL over a circular cone



DNS of ZPG Cold-Wall Hypersonic TBLs

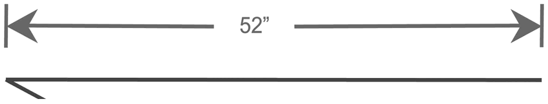
Geometry & Flow Conditions

- Freestream and wall-temperature conditions match those of CUBRC experiment
  - $M_\infty = 11.1$, $T_w = 300$ K, $T_w/T_r = 0.2$
  - Flat plate geometry: $0 \text{ m} \leqq x \leqq 1.3 \text{ m}$ (52 inches)

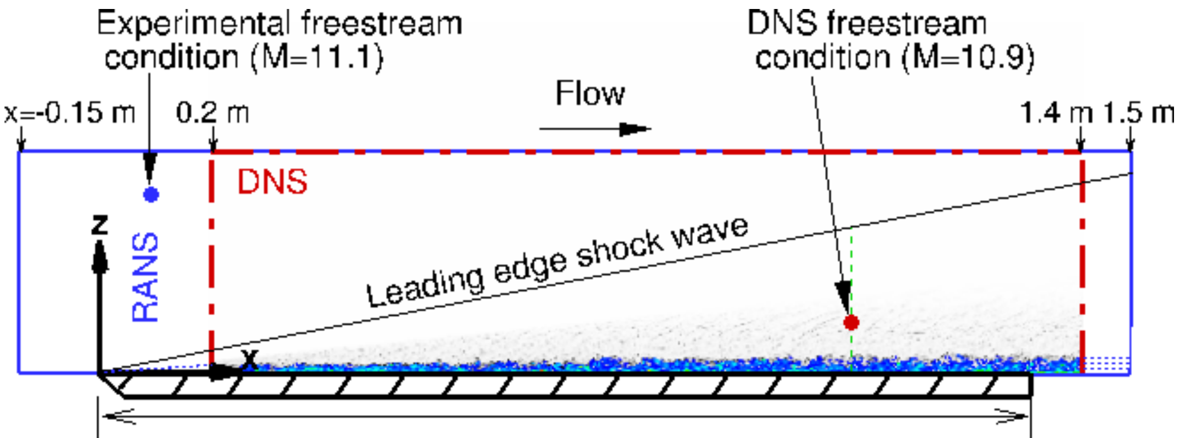


CUBRC experiments, Run 7

- "Embedded" DNS method
  - DNS inflow extracted from a full-domain RANS
    - RANS domain ($-0.15 \text{ m} \leqq x \leqq 1.5 \text{ m}$)
  - DNS domain enclosed in RANS domain
    - DNS domain ($0.2 \text{ m} \leqq x \leqq 1.4 \text{ m}$)
    - DNS domain covers the portion of the flat plate with a fully turbulent boundary layer in the experiment



- Flat Plate only
- 0 deg angle of attack

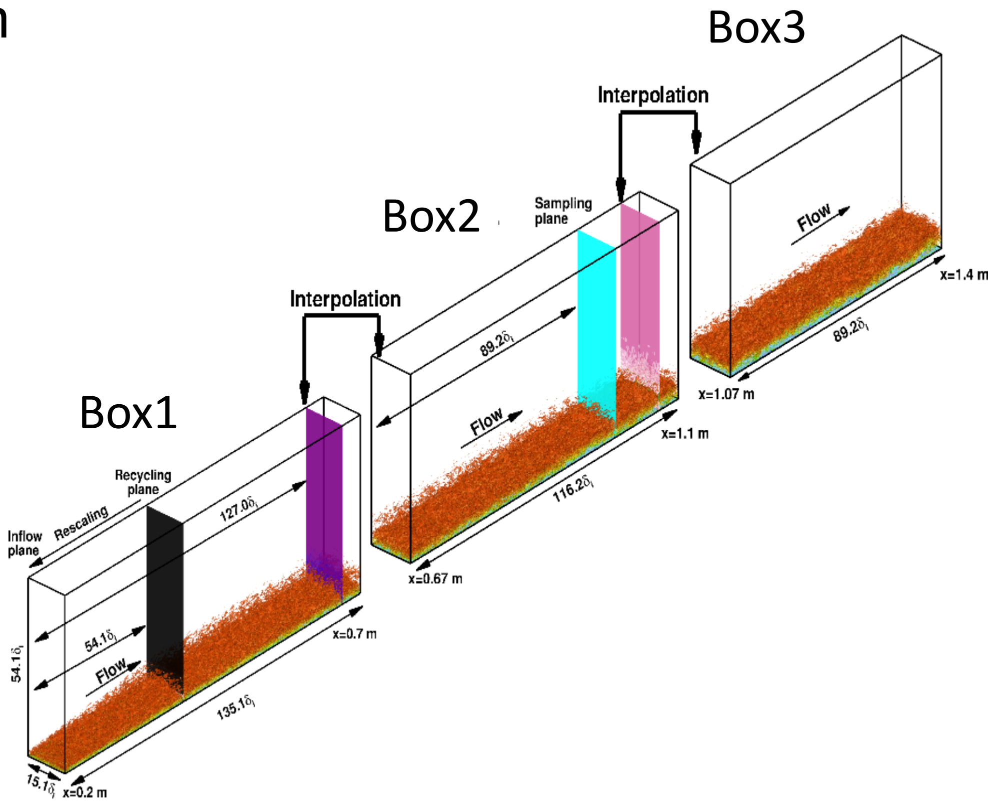


Flat plate geometry for CUBRC run 7, X_L=1.3 m

DNS of ZPG Cold-Wall Hypersonic TBLs

DNS Methodology

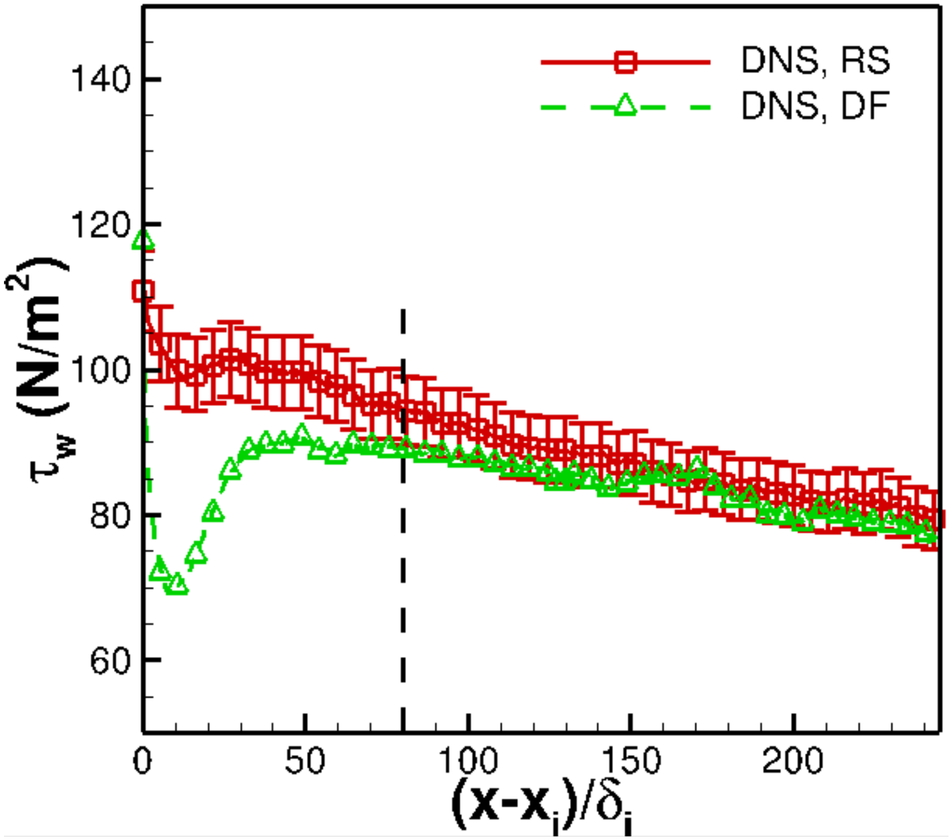
- DNS solves 3D compressible Navier-Stokes equations in conservative form
  - 7th order WENO (Jiang & Shu 1996)
  - rescaling/recycling method for inflow turbulence generation (Xu & Martin 2004)
  - carried out in 3 stages involving overlapping streamwise domains
    - large streamwise domain size of L_x/δ_i = 324.3 to minimize any artificial effects due to inflow turbulence generation
    - sufficiently long sampling duration ensures the convergence of selected high-order turbulence statistics

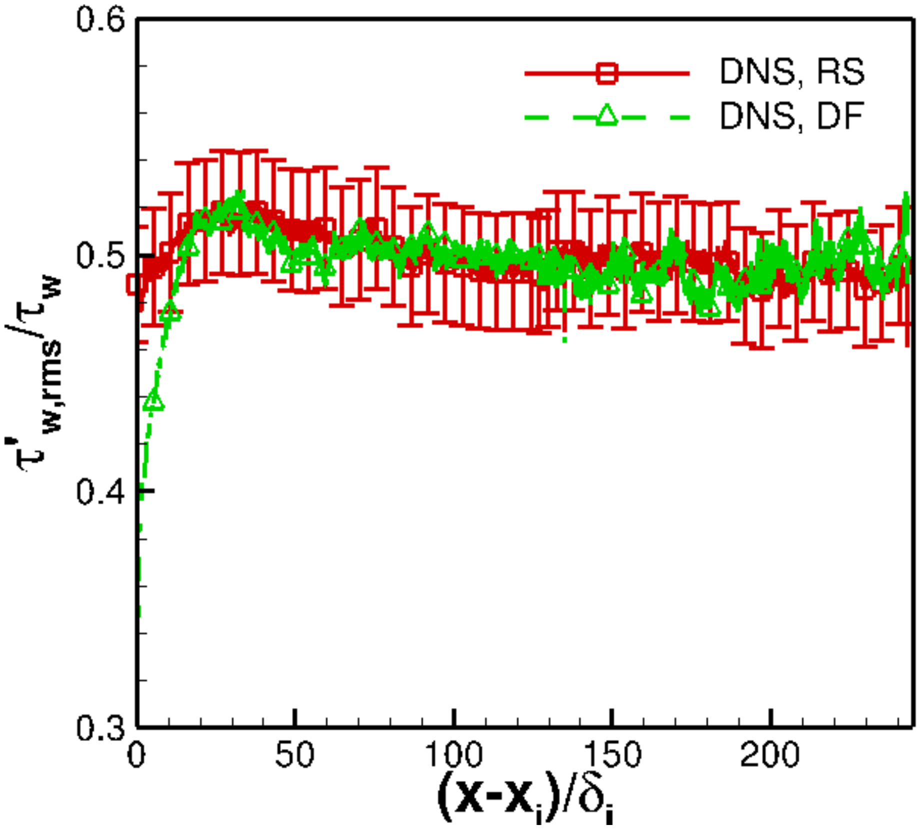


Case	$N_x \times N_y \times N_z$	x_{range}, m	L_x/δ_i	L_y/δ_i	L_z/δ_i	Δx^+	Δy^+	Δz^+_{min}	Δz^+_{max}	N_f	$T_f u_\tau/\delta$
Box1	$5000 \times 400 \times 690$	$0.2 - 0.7$	135.1	15.1	54.1	7.4	10.3	0.43	4.4	428	3.07
Box2	$4301 \times 400 \times 690$	$0.67 - 1.1$	116.2	15.1	54.1	7.4	10.3	0.43	4.4	281	2.02
Box3	$3300 \times 400 \times 690$	$1.07 - 1.4$	89.2	15.1	54.1	7.4	10.3	0.43	4.4	241	1.73

DNS of ZPG Cold-Wall Hypersonic TBLs

Assessment of Inflow BC

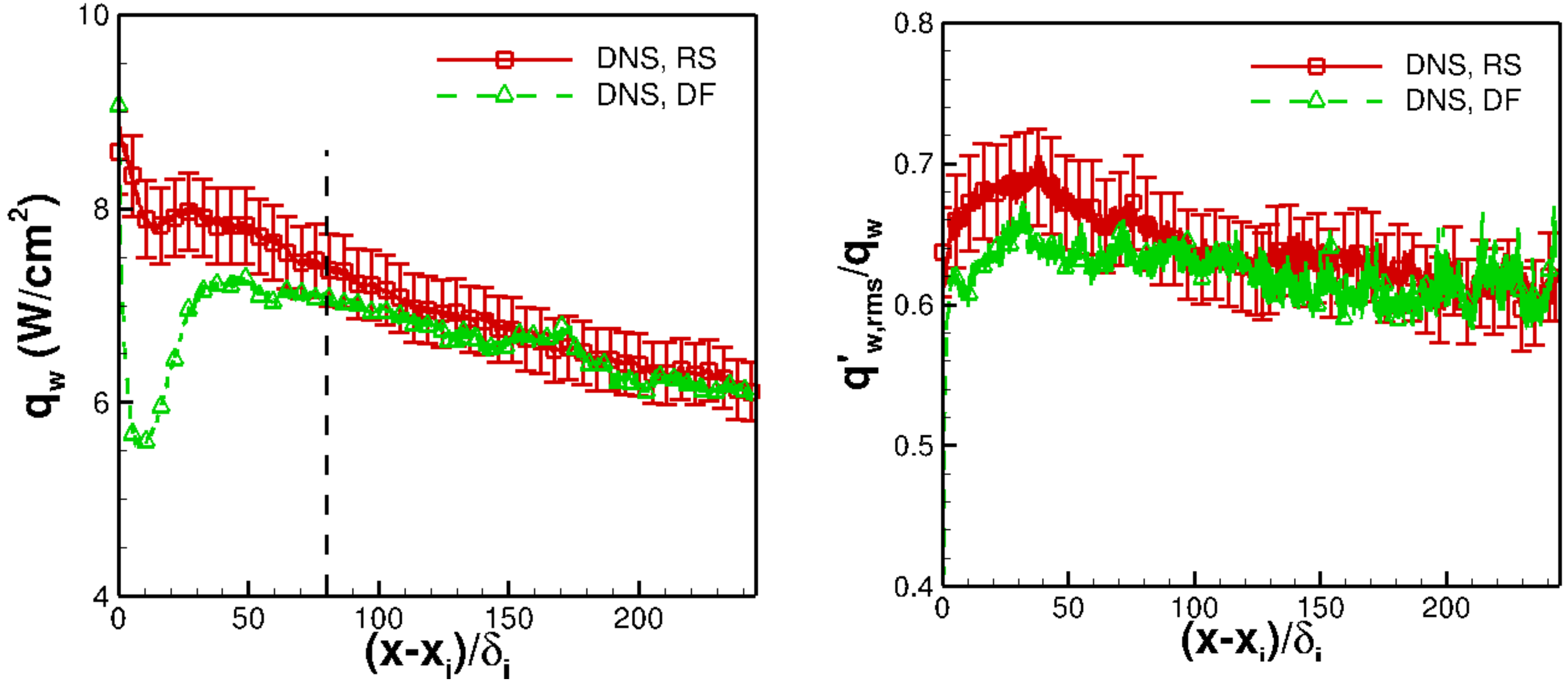




- ➢ Both mean and RMS fluctuations of wall shear stress (q_w) predicted by rescaling (RS) and digital-filtering (DF) inflow methods agree within 5% for $x-x_i > 80\delta_i$.

DNS of ZPG Cold-Wall Hypersonic TBLs

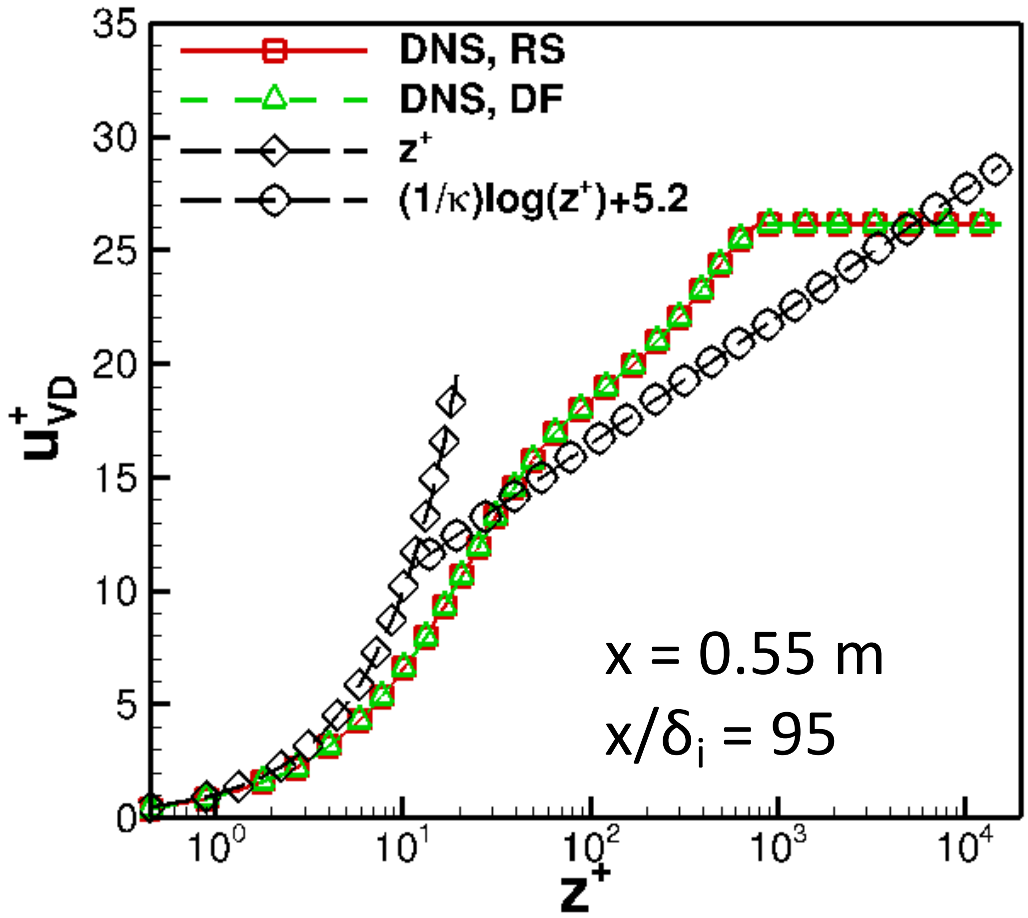
Assessment of Inflow BC

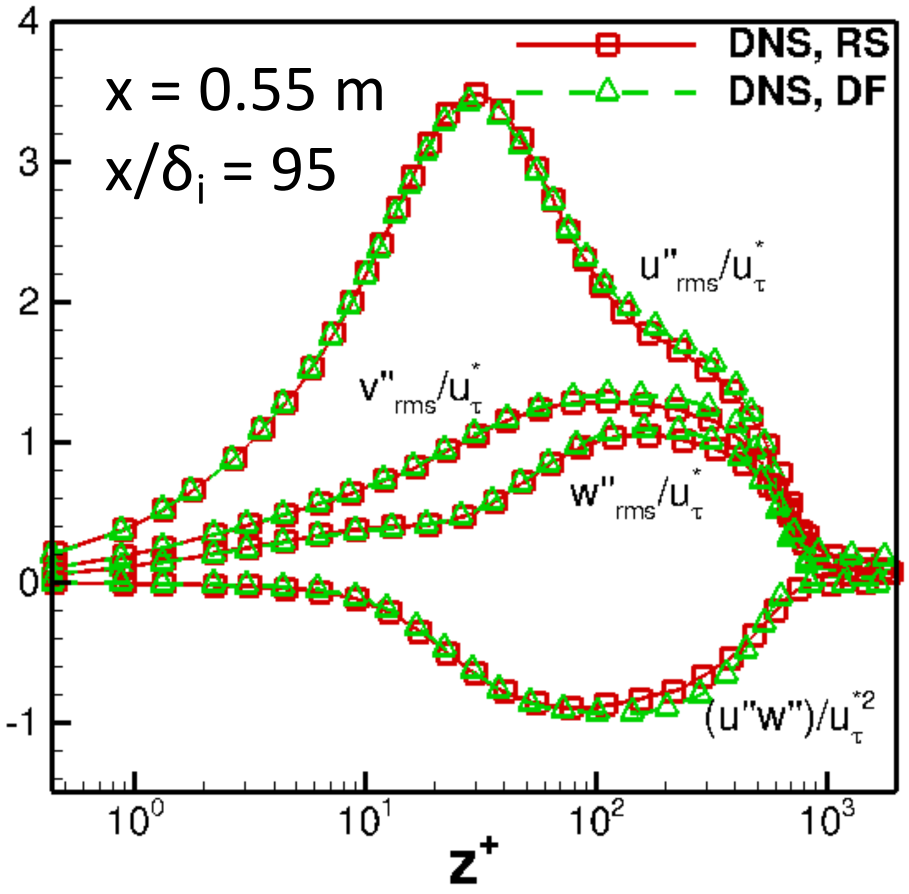


- ➢ Both mean and RMS fluctuations of wall heat flux (q_w) predicted by rescaling (RS) and digital-filtering (DF) inflow methods agree within 5% for $x-x_i > 80\delta_i$.

DNS of ZPG Cold-Wall Hypersonic TBLs

Assessment of Inflow BC

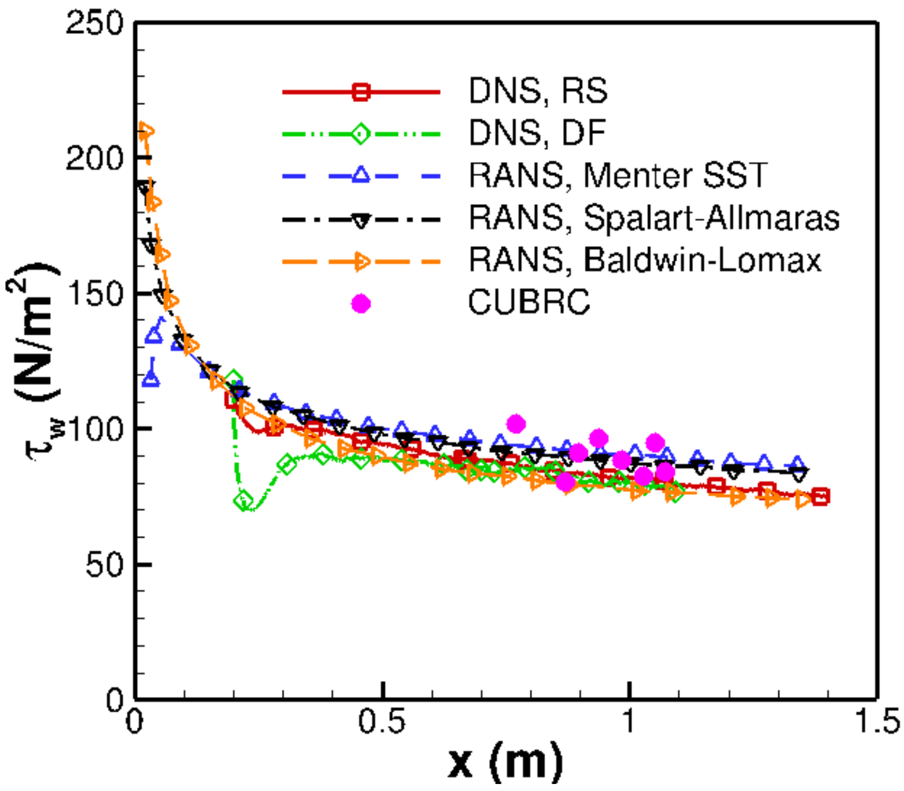


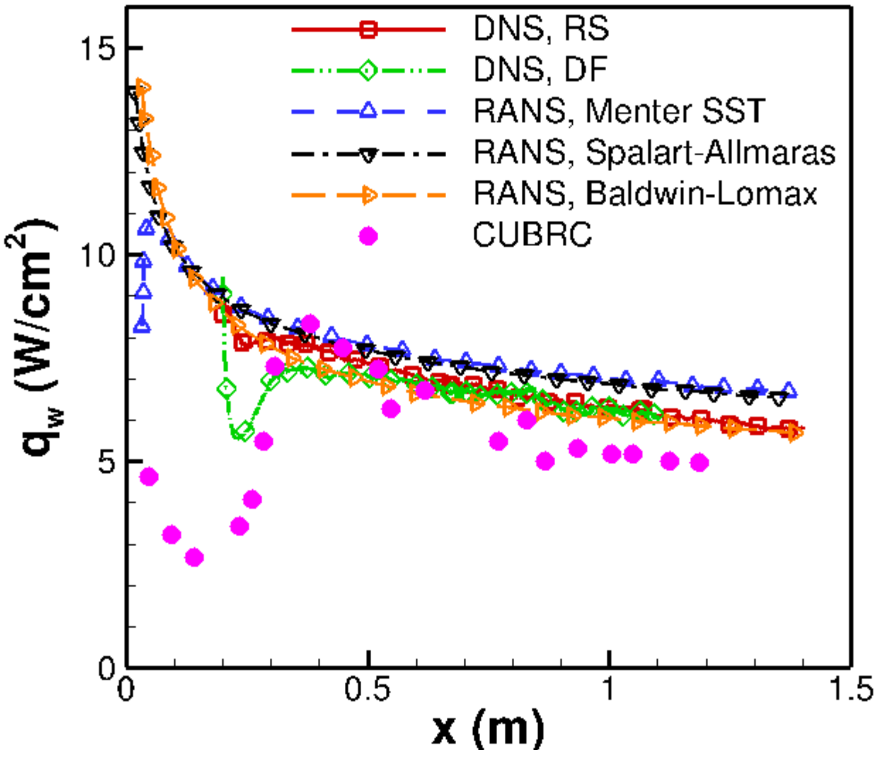


- Good comparisons related to mean velocity and RMS velocity fluctuation profiles at x = 0.55 m ($x/\delta_i = 95$) between two DNS with different inflow techniques

DNS of ZPG Cold-Wall Hypersonic TBLs

Comparison with Experiment





- Wall shear stress (τ_w) compares well with experiment and RANS data
- Wall heat flux (q_w) compares well with the experiment in the post-transition region up to x ≈ 0.8 m
- DNS overpredicts measured q_w for x > 0.8 m but is comparable to the Baldwin-Lomax model

DNS of ZPG Cold-Wall Hypersonic TBLs

Boundary Layer Parameters

- Effect of Reynolds number is investigated by comparing boundary-layer profiles at three downstream locations (x_a = 0.55 m, 1.0 m, 1.35 m) for Case M11Tw020
  - Three profiles referred to as M11BL1, M11BL2, and M11BL3, respectively
  - Friction Reynolds number Re_τ ranges from 631 to 1138
- Effect of Mach number is investigated by comparing Case M11Tw020 with a Mach 14 simulation (Case M14Tw018)
  - $T_w/T_r \cong 0.2$ for both Mach numbers
  - $Re_\tau \cong 630$ for M11BL1 and M14Tw018

Case	M_∞	U_∞ (m/s)	ρ_∞ (kg/m^3)	T_∞ (K)	T_w (K)	T_w/T_r	δ_i (mm)
M11Tw020	10.9	1778.4	0.103	66.5	300.0	0.20	3.7
M14Tw018	13.64	1882.2	0.017	47.4	300.0	0.18	18.8

Case	x_a (m)	$(x_a - x_i)/\delta_i$	Re_θ	Re_τ	Re_{δ_2}	Re_τ^*	θ, mm	H	δ, mm	z_τ, μm	u_τ, m/s	$-B_q$	M_τ
M11BL1	0.55	95	9080	631	2204	5536	0.22	25.5	8.0	12.7	63.6	0.164	0.183
M11BL2	1.00	216	14143	926	3419	8167	0.35	26.1	12.6	13.6	60.3	0.154	0.174
M11BL3	1.35	311	18164	1138	4390	10035	0.45	26.1	16.0	14.1	58.1	0.148	0.167
M14Tw018	3.7	199.3	14258	633	2330	9796	1.33	38.4	65.0	102.8	67.3	0.19	0.19

DNS of ZPG Cold-Wall Hypersonic TBLs

Mean Velocity Scaling

van-Driest (VD) velocity scaling

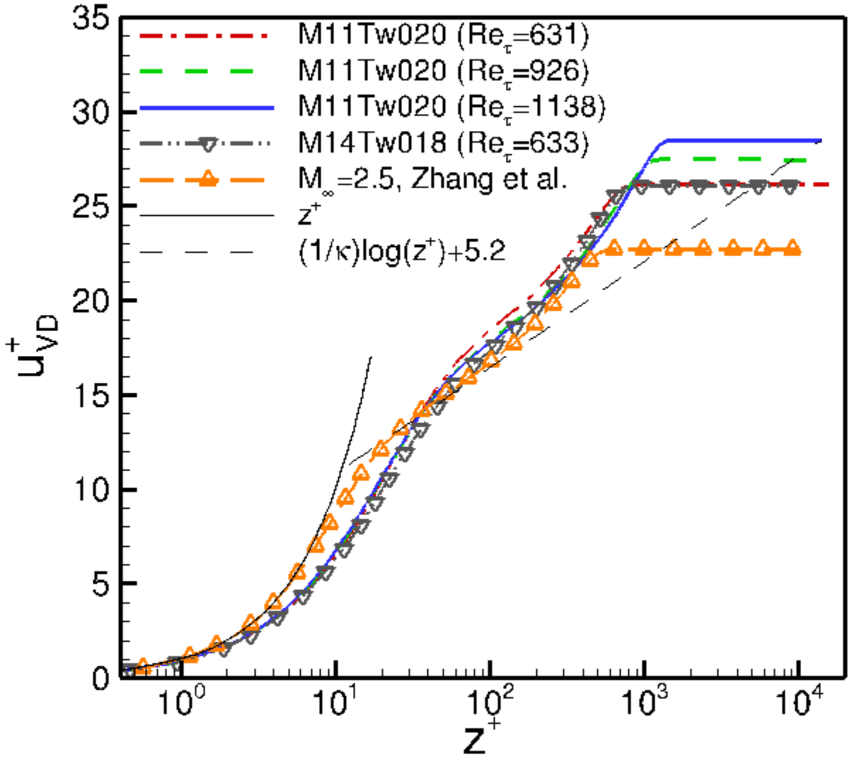
$$u^+_{\rm VD} = \frac{1}{u_\tau}\int_0^{\bar u} (\bar\rho/\bar\rho_w)^{1/2}\, \mathrm{d}\bar u$$

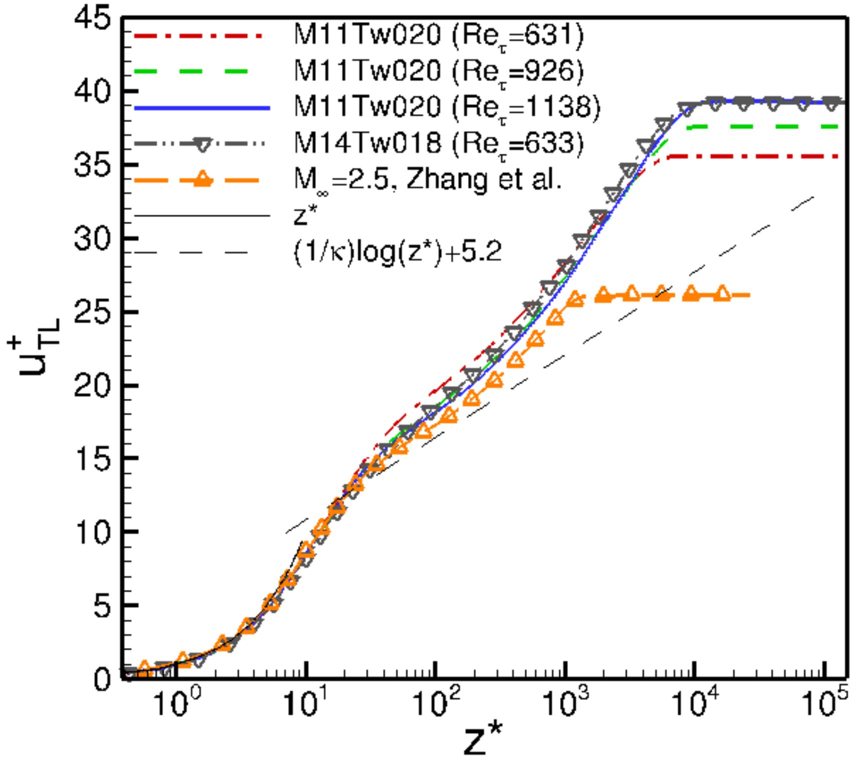
$+$ = variable in inner wall units

Trettel-Larsson (TL) velocity scaling

$$u^+_{\rm TL} = \int_0^{u^+} \left(\frac{\bar\rho}{\rho_w}\right)^{1/2}\left[1+\frac{1}{2}\frac{1}{\bar\rho}\frac{d\bar\rho}{dz}z - \frac{1}{\bar\mu}\frac{d\bar\mu}{dz}z\right] \mathrm{d}u^+$$

$*$ = variable in semilocal units

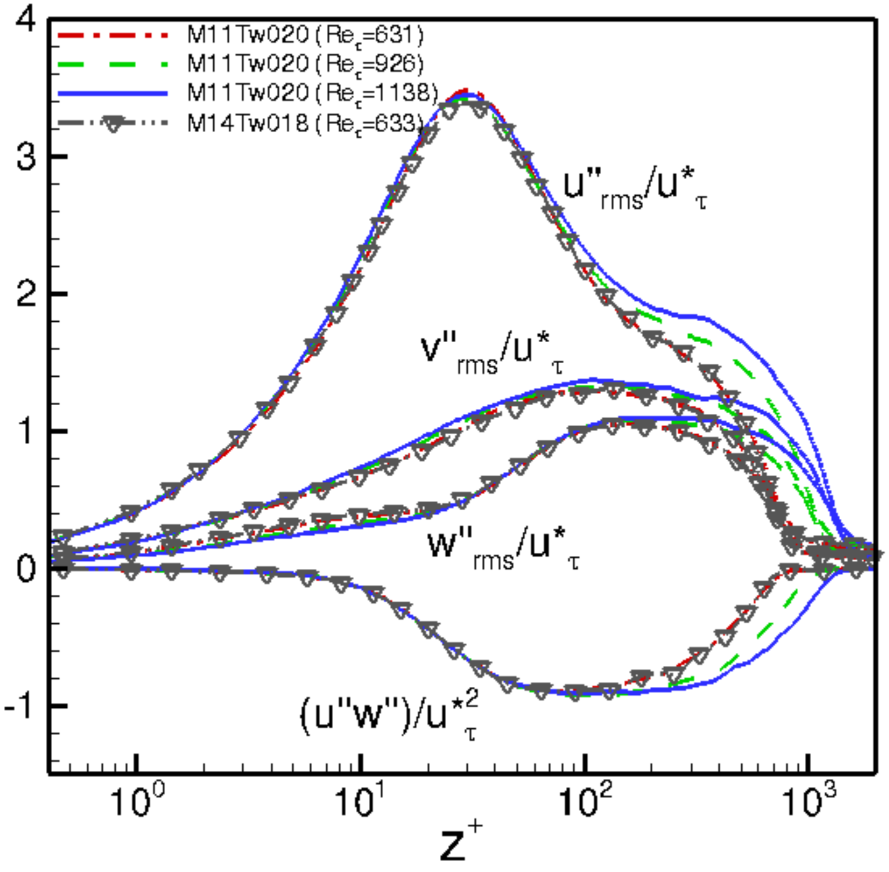


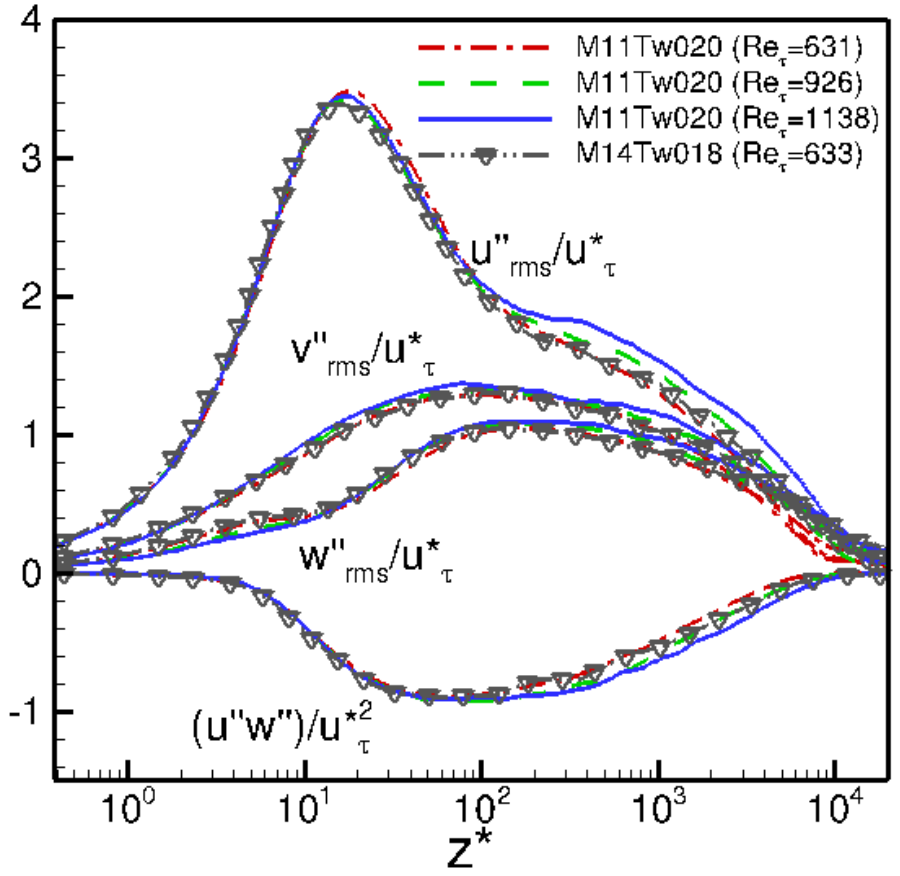


- u^+_{VD} shows reduced viscous sublayer slope compared to adiabatic wall case
- u^+_{TL} shows a better collapse in the viscous sublayer for wall-cooling cases
- Both u^+_{VD} and u^+_{TL} show similar scatter in the log-law region

DNS of ZPG Cold-Wall Hypersonic TBLs

Turbulent Intensity and Reynolds Stress





➢ The semilocal scaling ($z^* = z/z^*_\tau$) better collapses the turbulence intensities than the classic viscous length ($\mathrm{z}^+ = \mathrm{z}/\mathrm{z}_\tau = z/(\nu_w/u_\tau)$)

DNS of ZPG Cold-Wall Hypersonic TBLs

Turbulent Kinetic Energy (TKE) Budgets

$$\frac{D(\bar{\rho}\,\tilde{k})}{Dt} = P + TT + \Pi - \phi + D + ST$$

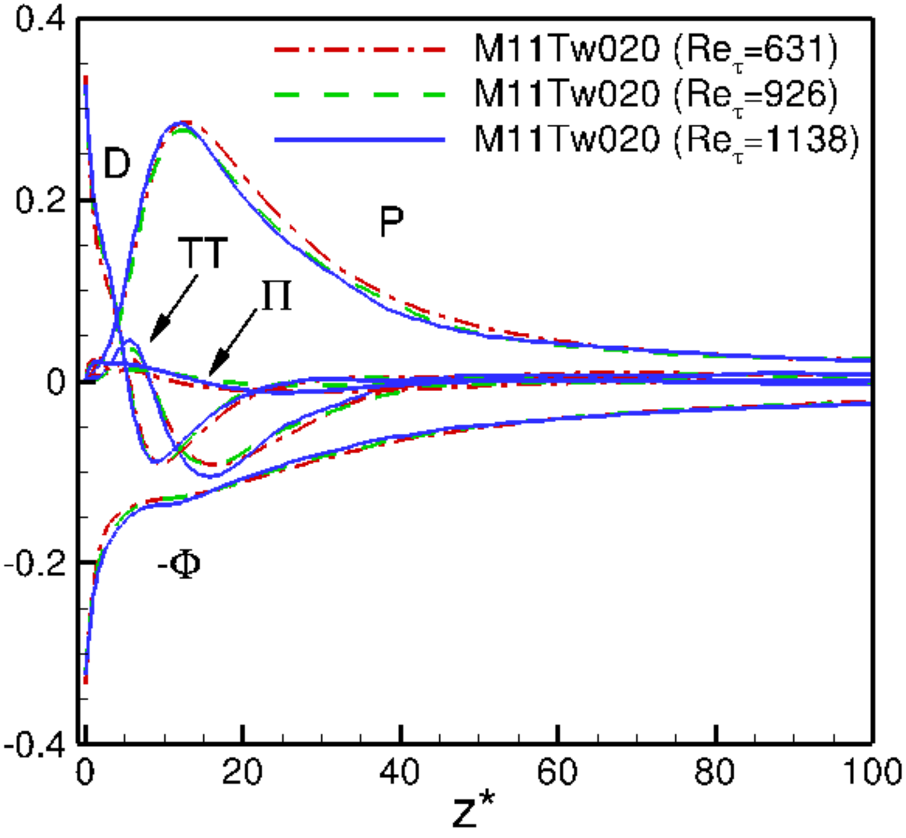
$+$ = variable in inner wall units, $(\cdot)^+ \equiv (\cdot)/z_\tau$

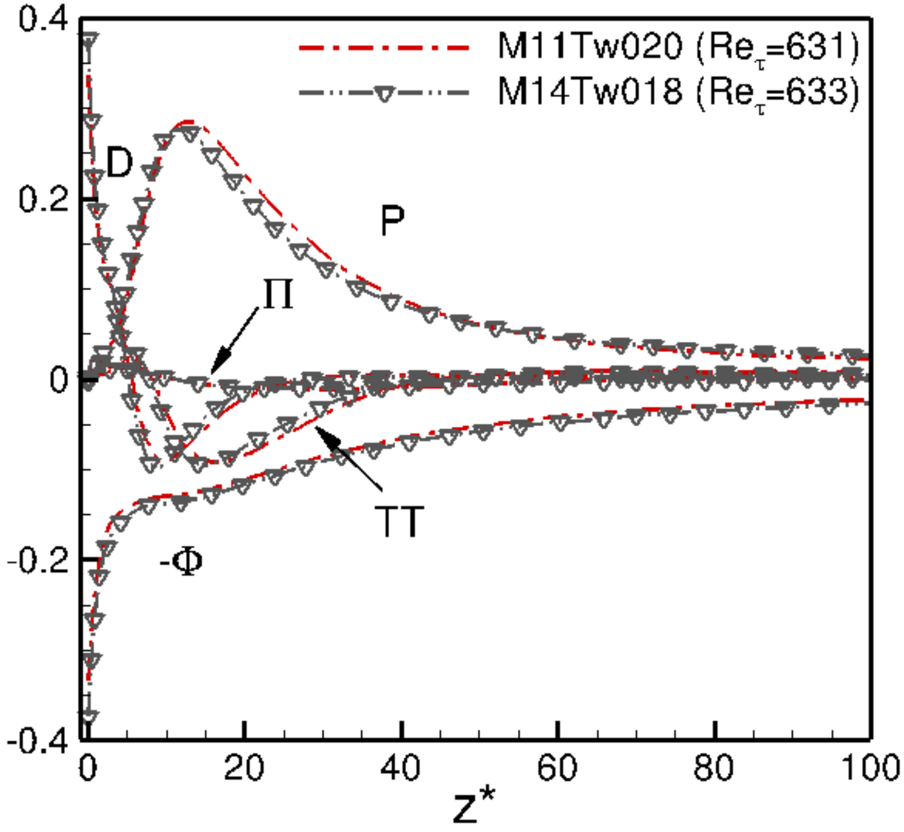
$*$ = variable in semilocal units, $(\cdot)^* \equiv (\cdot)/z_\tau^*$

$$P = -\overline{\rho u_i'' u_k''}\,\frac{\partial \widetilde{u_i}}{\partial x_k} \qquad \phi = \overline{\tau_{ik}'\,\frac{\partial u_i''}{\partial x_k}}$$

$$TT = -\frac{\partial}{\partial x_k}\left(\frac{1}{2}\overline{\rho u_i'' u_i'' u_k''}\right) \qquad D = \frac{\partial}{\partial x_k}\left(\overline{\tau_{ik}'' u_i''}\right)$$

$$\Pi = \Pi^t + \Pi^d = -\frac{\partial}{\partial x_i}\left(\overline{p' u_i''}\right) + \overline{p'\,\frac{\partial u_i''}{\partial x_i}} \qquad ST = \overline{u_i''}\left(\frac{\partial \bar{\tau}_{ik}}{\partial x_k} - \frac{\partial \bar{p}}{\partial x_i}\right) - \bar{\rho}\,\tilde{k}\,\frac{\partial \tilde{u}_k}{\partial x_k}$$



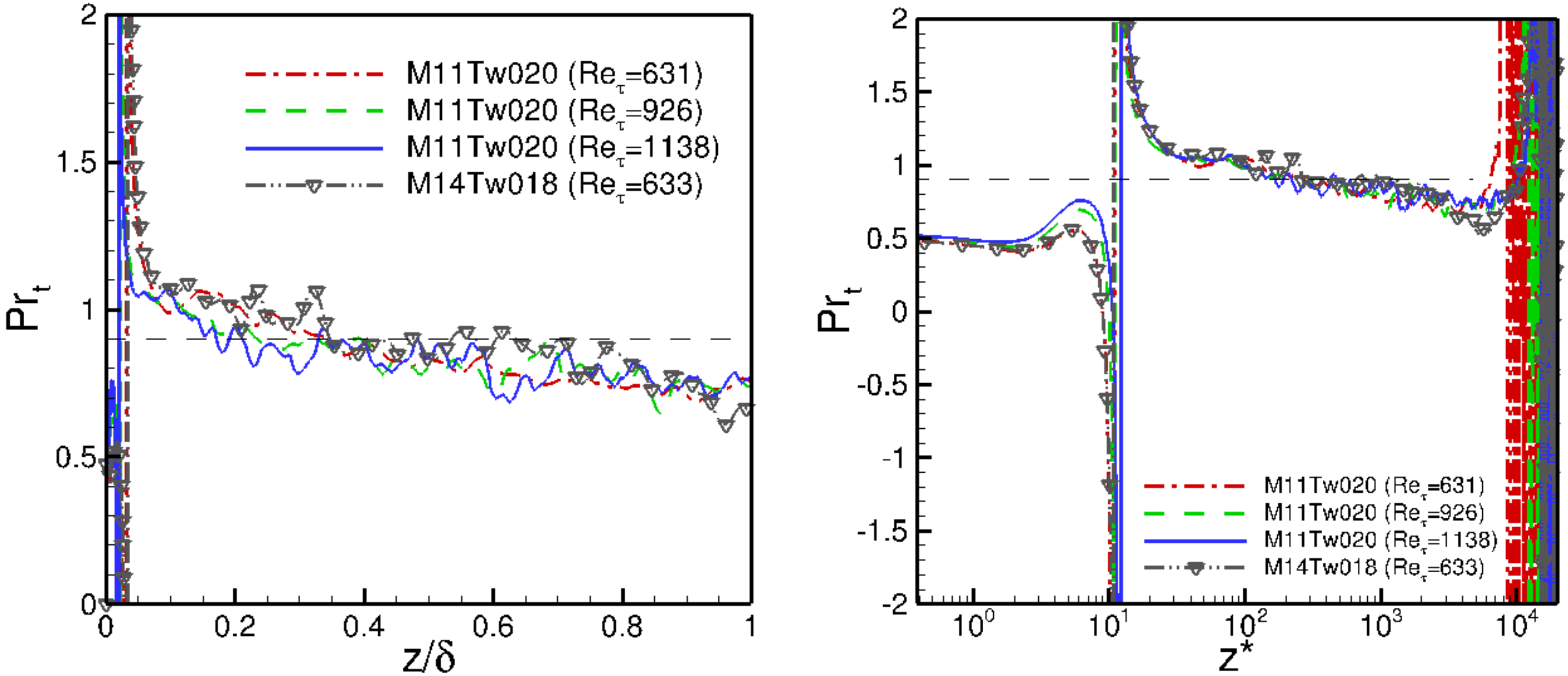


- ➢ The semilocal scaling successfully collapses TKE budget terms among the various cases with different Mach number and Reynolds number conditions

DNS of ZPG Cold-Wall Hypersonic TBLs

Turbulent Prandtl Number

Turbulent Prandtl number: $$Pr_t \equiv \frac{\overline{\rho u''w''}(\partial\tilde{T}/\partial z)}{\overline{\rho w''T''}(\partial\tilde{u}/\partial z)}$$



- Turbulent Prandtl number is approximately 0.9 in most of the boundary layer
- Constant Pr_t fails in the near-wall region
    - Large overshoot and sign change happen in the near wall region

DNS of ZPG Cold-Wall Hypersonic TBLs

Assessment of Turbulent Heat Flux Models

- DNS data is used to assess turbulent heat flux formulations for RANS
  - Constant-Pr$_t$ formulation (Wilcox 2006)

$$q_i^T = \overline{\rho h'' u_i''} \approx -\frac{C_p \widetilde{\mu}_t}{Pr_t} \frac{\partial \widetilde{T}}{\partial x_i}$$

  - Algebraic energy flux (AEF) formulation (Bowersox, JFM 2009)

$$a_{ik} \vartheta_k^T = b_i$$

with $\vartheta_i^T = \overline{\rho e'' u_i''}$ (Turbulent energy flux)

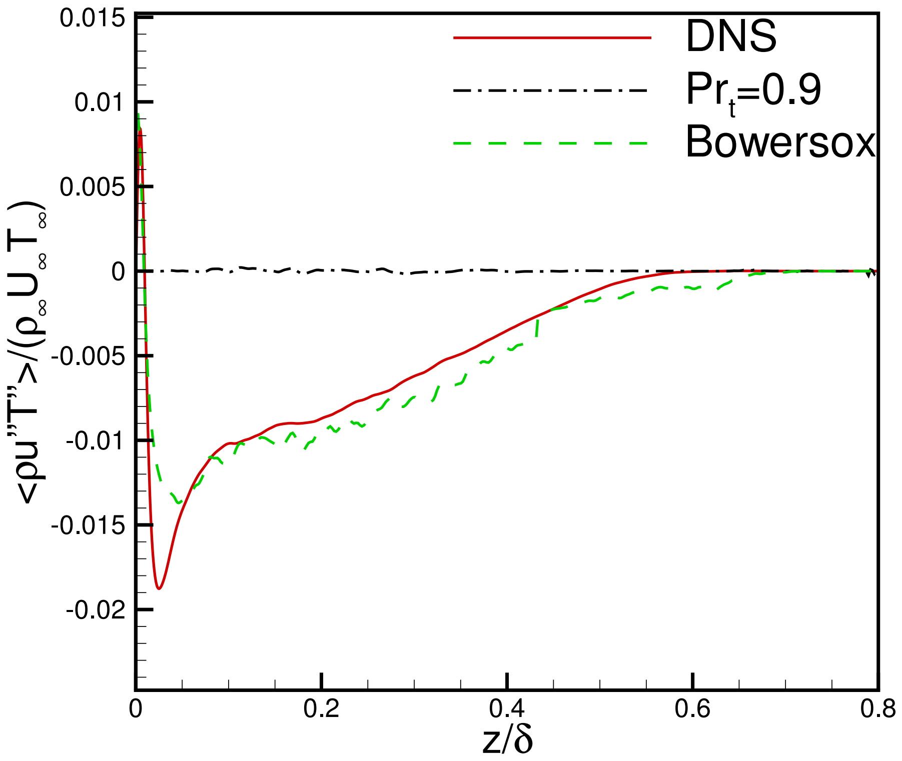
$$a_{ik} = \delta_{ik} / \tau_\vartheta + \zeta_{ik}$$

$$b_i = \tau_{ik}^T \tilde{\psi}_{,k}$$

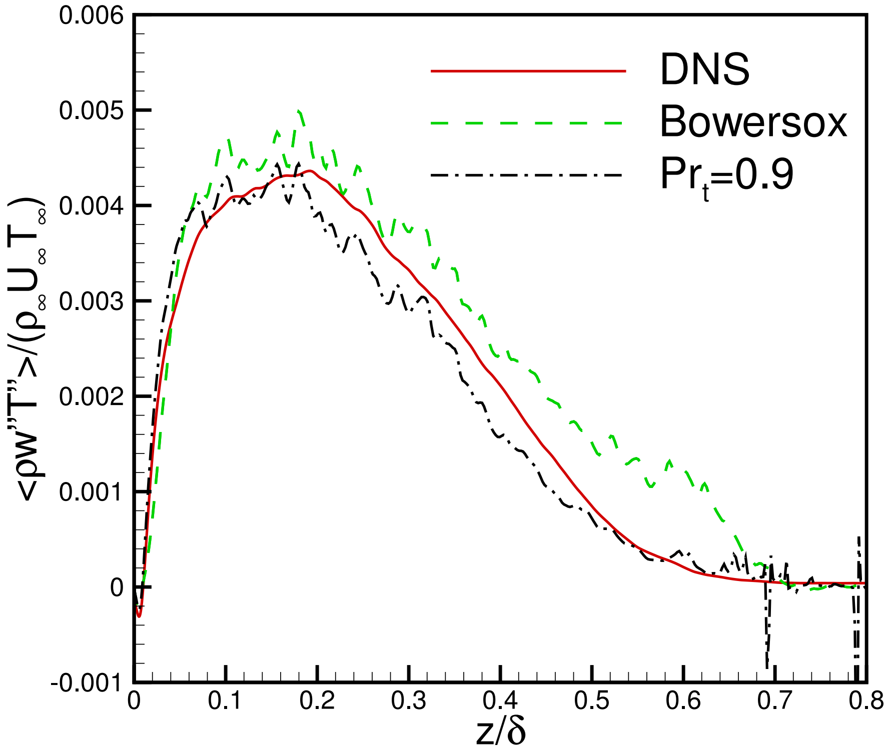
DNS of ZPG Cold-Wall Hypersonic TBLs

Assessment of Turbulent Heat Flux Models (a priori study)

Streamwise turbulent heat flux $\overline{\rho u''T''}$



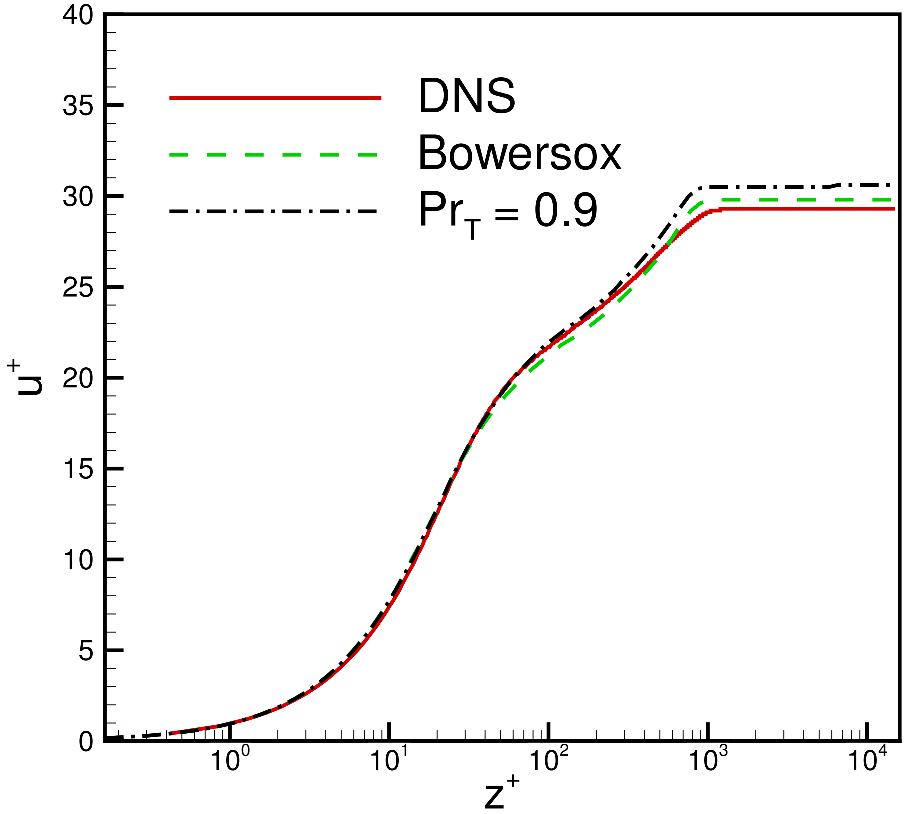
Wall-normal turbulent heat flux $\overline{\rho w''T''}$.

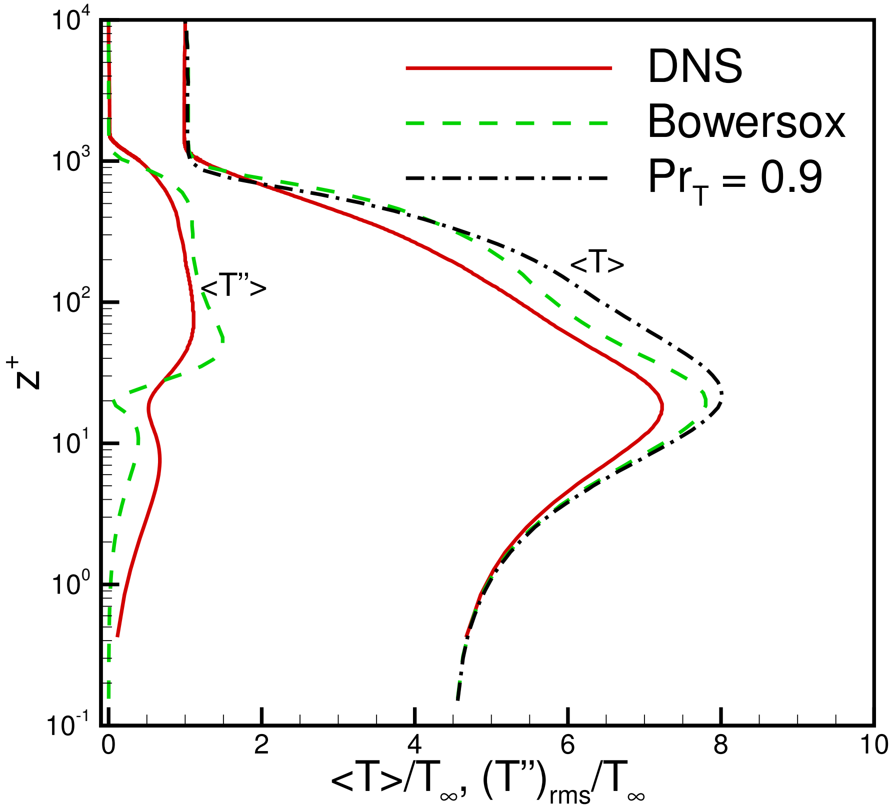


- A priori assessment of turbulent heat flux formulations by using mean flow quantities and Reynolds stresses from the DNS showed that
  - The AEF formulation of Bowersox gives better predictions of the streamwise turbulent heat flux than the constant-Pr_t model
  - both models give similarly good predictions of the wall-normal turbulent heat flux

DNS of ZPG Cold-Wall Hypersonic TBLs

Assessment of Turbulent Heat Flux Models (a posteriori study)





- A posteriori assessment by comparing DNS with RANS predictions based on two different turbulent heat flux formulations showed that
    - AEF formulation of Bowersox yields somewhat improved prediction of the temperature profiles while keeping a good prediction of the velocity field

DNS of ZPG Cold-Wall Hypersonic TBLs

Summary

- ☐ DNS of flat-plate, zero-pressure-gradient (ZPG) turbulent boundary layers were presented for high Mach numbers (M_∞ = 11, 14) and a highly cooled wall ($T_w/T_r \sim 0.2$)

- ☐ Assessment of the DNS data was conducted by comparing runs with different inflow methods and by comparing DNS against experiments
  - good comparisons between turbulent statistics with rescaling (RS) and digital-filtering (DF) inflow methods after approximately $80\delta_i$ from the inflow
  - DNS showed good comparisons with those measured at CUBRC and those modeled with a Baldwin-Lomax model

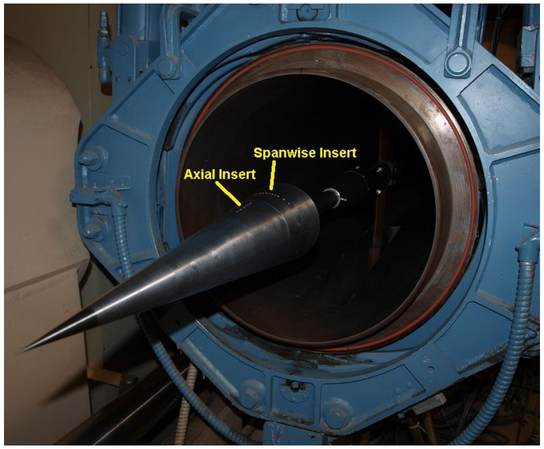
- ☐ DNS results confirmed the validity of Morkovin's hypothesis for Mach numbers up to 14 and frictional Reynolds numbers (Re_τ) up to 1200

- ☐ A priori and a posteriori assessments of turbulent heat flux models using DNS data showed that
  - the algebraic energy flux (AEF) formulation gives better predictions of the streamwise turbulent heat flux than the constant-Pr_t model while both models give similarly good predictions of the wall-normal turbulent heat flux
  - the AEF model improves the prediction of the temperature profiles while keeping a good prediction of the velocity field

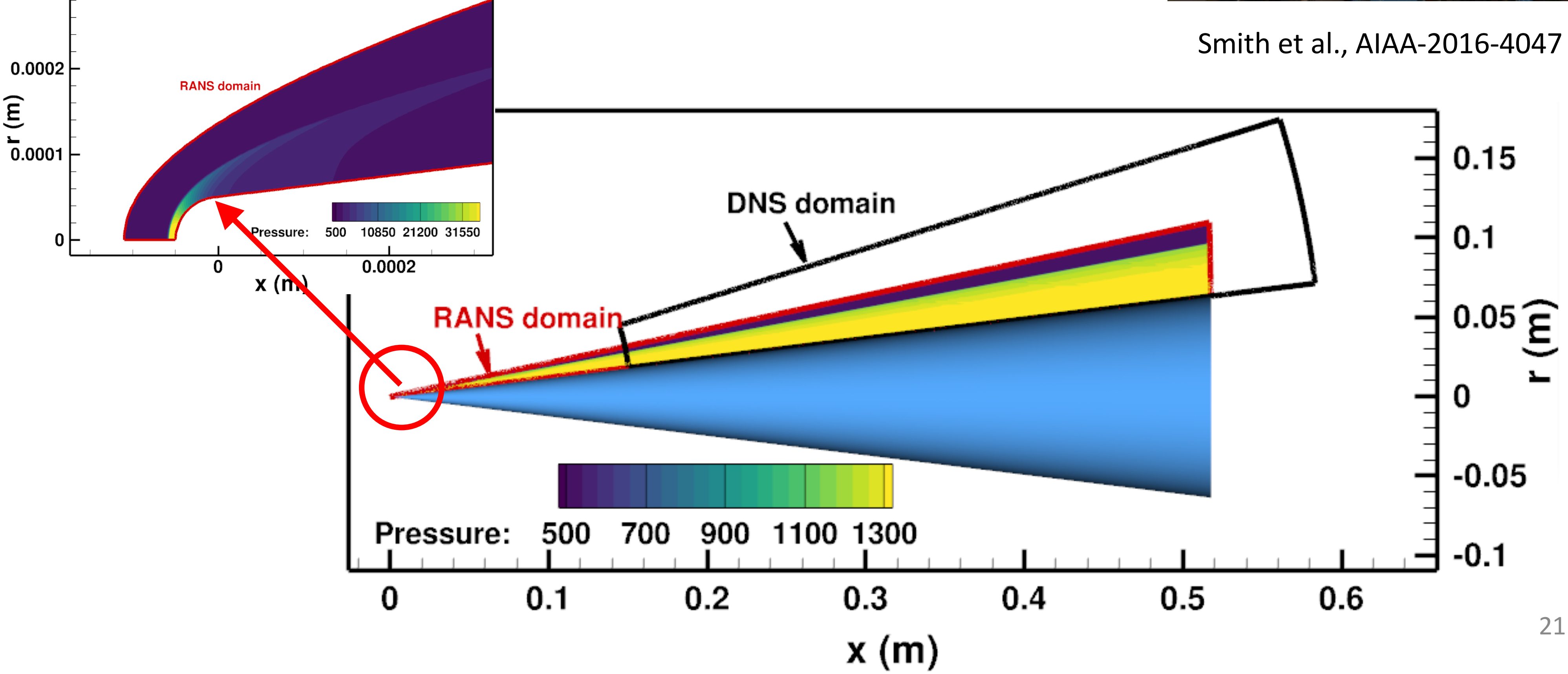
DNS of Cone in a Hypersonic Wind Tunnel

Geometry & Flow Conditions

- Cone geometry and flow conditions match those of Sandia HWT-8
  - 7-deg half-angle cone, L = 0.517 m, D = 0.127 m, r_n = 0.05 mm
  - p_0 = 4692 kPa, T_0 = 617 K, Re = 13.4 ×10^6/m
- DNS domain consists of a section of the cone
  - DNS inflow extracted from a RANS with the full-cone geometry
  - Digital filtering method for generating inflow turbulence



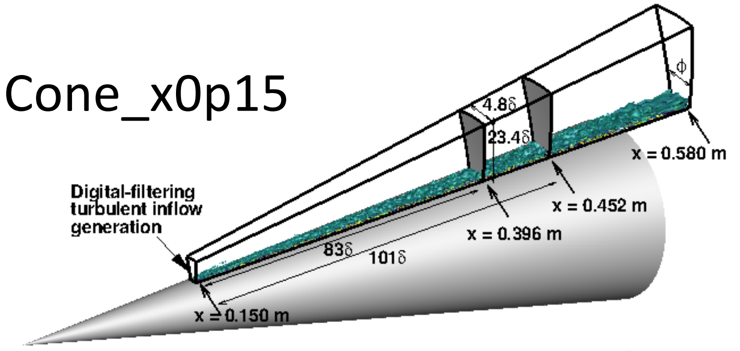
Smith et al., AIAA-2016-4047

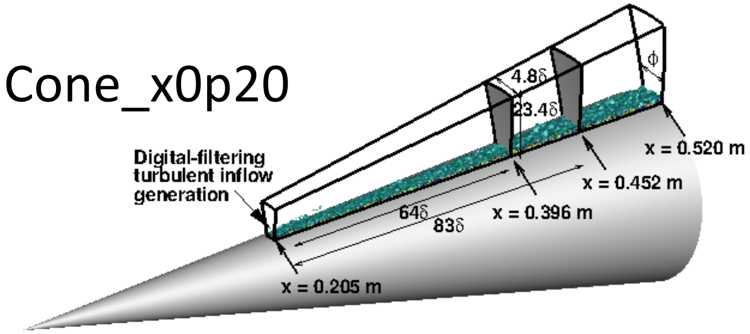


DNS of Hypersonic Wind Tunnel Cone

Assessment of Inflow BC and Flow Solvers

- ☐ DNS with WENO code
  - 7^{th}-order WENO method
  - Laminar-turbulent transition bypassed
    - Inflow turbulence generated with digital-filtering method
  - Two DNS runs performed to demonstrate insensitivity of the computed p'_w to the inflow locations





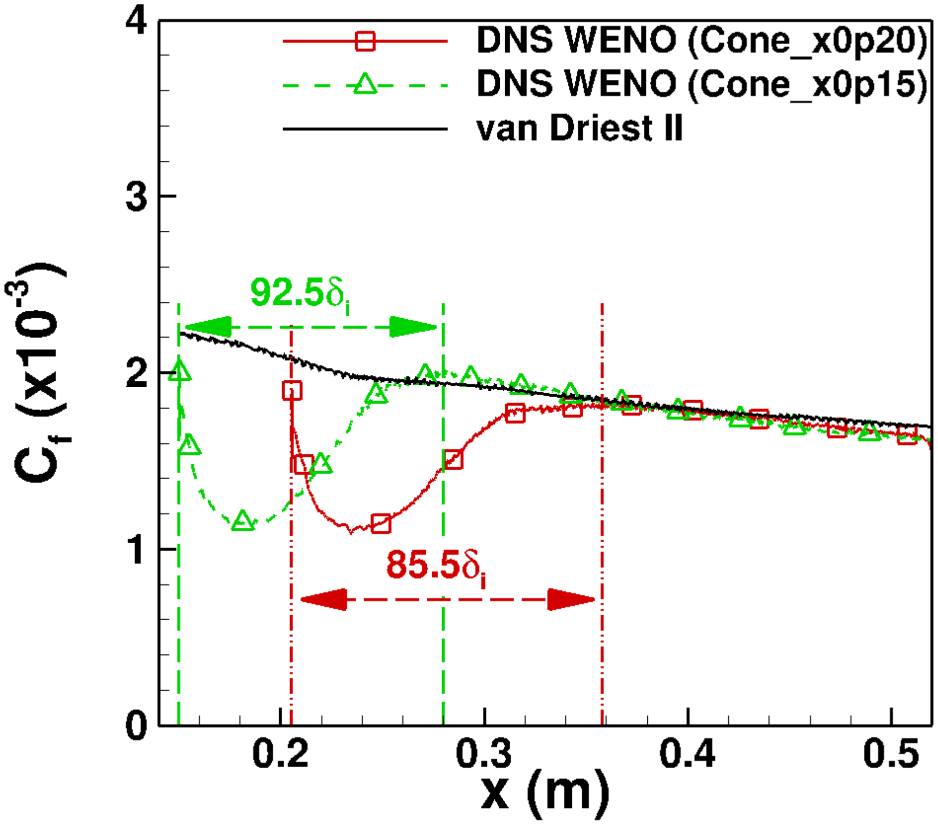
- ☐ DNS with Sandia's SPARC code
  - 2^{nd}-order finite-volume code
  - Laminar-turbulent transition included
    - Turbulent BL generated by the laminar breakdown of second-mode waves
  - conducted with significantly larger domain & finer meshes than WENO DNS

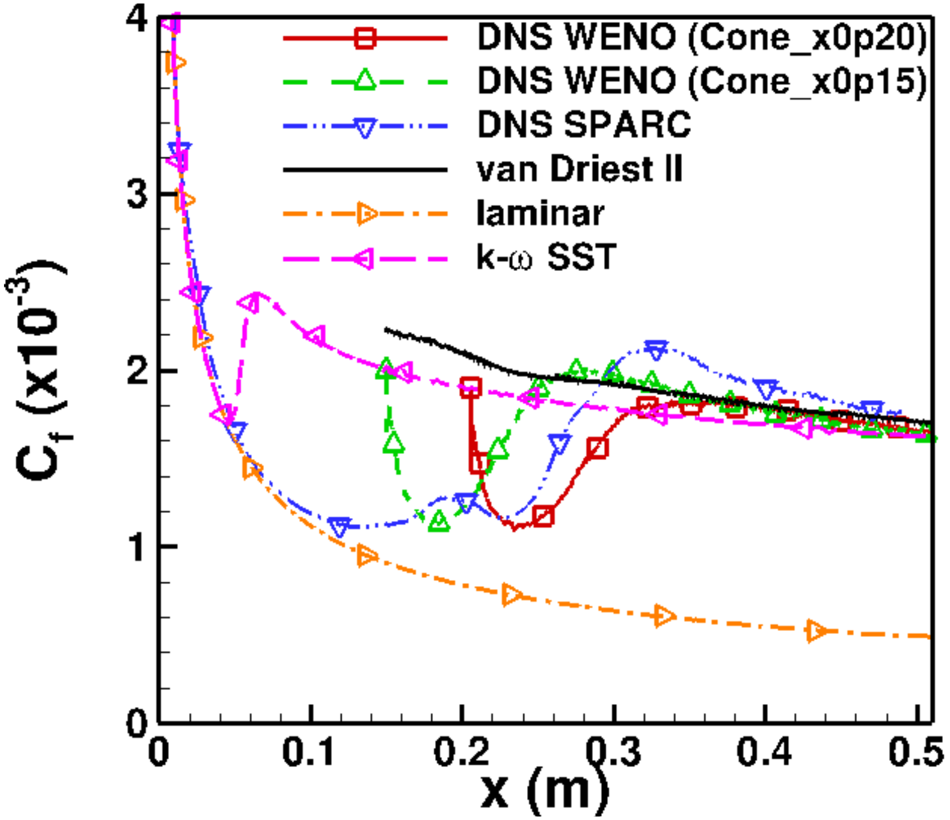
Case	x_{range} *(m)*	Θ *(deg)*	N_x X N_Θ X N_z	Δx^+	$(R\Delta\Theta)^+_w$	Δr^+_w	Δr^+_e
Cone_x0p15	**0.15** – 0.58	16.9	3840 x 160 x 200	5.2	4.6	0.45	4.4
Cone_x0p20	**0.205** – 0.52	16.9	3072 x 160 x 200	5.2	4.7	0.44	4.5
DNS SPARC	**0.0002** – 0.542	30.0	8600 x 460 x 700	3.93	2.69	0.35	0.59

Δx^+, $(R\Delta\Theta)^+_w$, Δr_w^+, Δr_∞^+ are evaluated using viscous length at $x \cong 0.396$ m

DNS of Hypersonic Wind Tunnel Cone

Assessment of Inflow BC and Flow Solvers



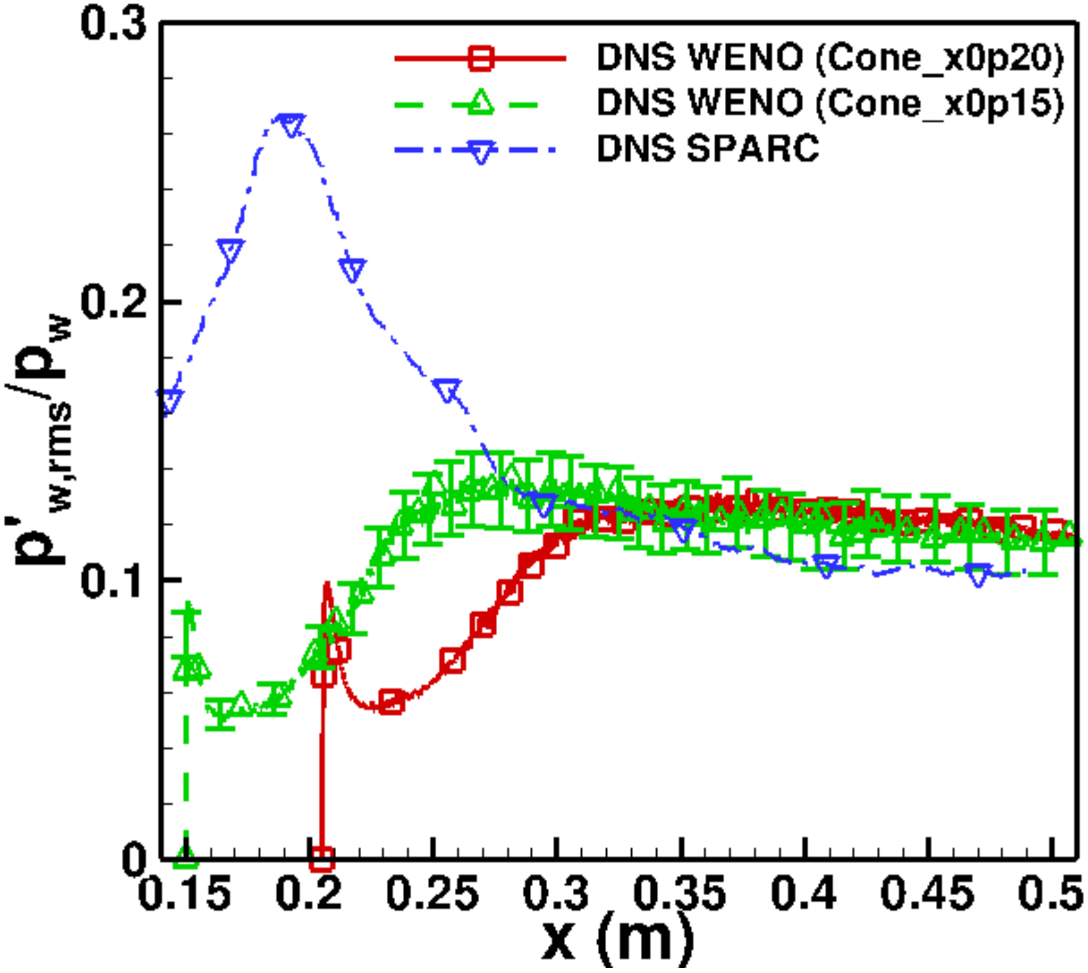


- ➢ C_f from the two WENO runs
  - ▪ converges within 5% of each other after $L_{adjust} \cong 0.15$ m
- ➢ C_f prediction with the SPARC code
  - ▪ matches that of the **laminar flow solution** in the pre-transitional region
  - ▪ converges to **the turbulent values** in the downstream portion of the computational box
- ➢ WENO and SPARC runs converge (within 5%) to van Driest II Theory and the pre-cursor RANS simulation after initial transient

DNS of Hypersonic Wind Tunnel Cone

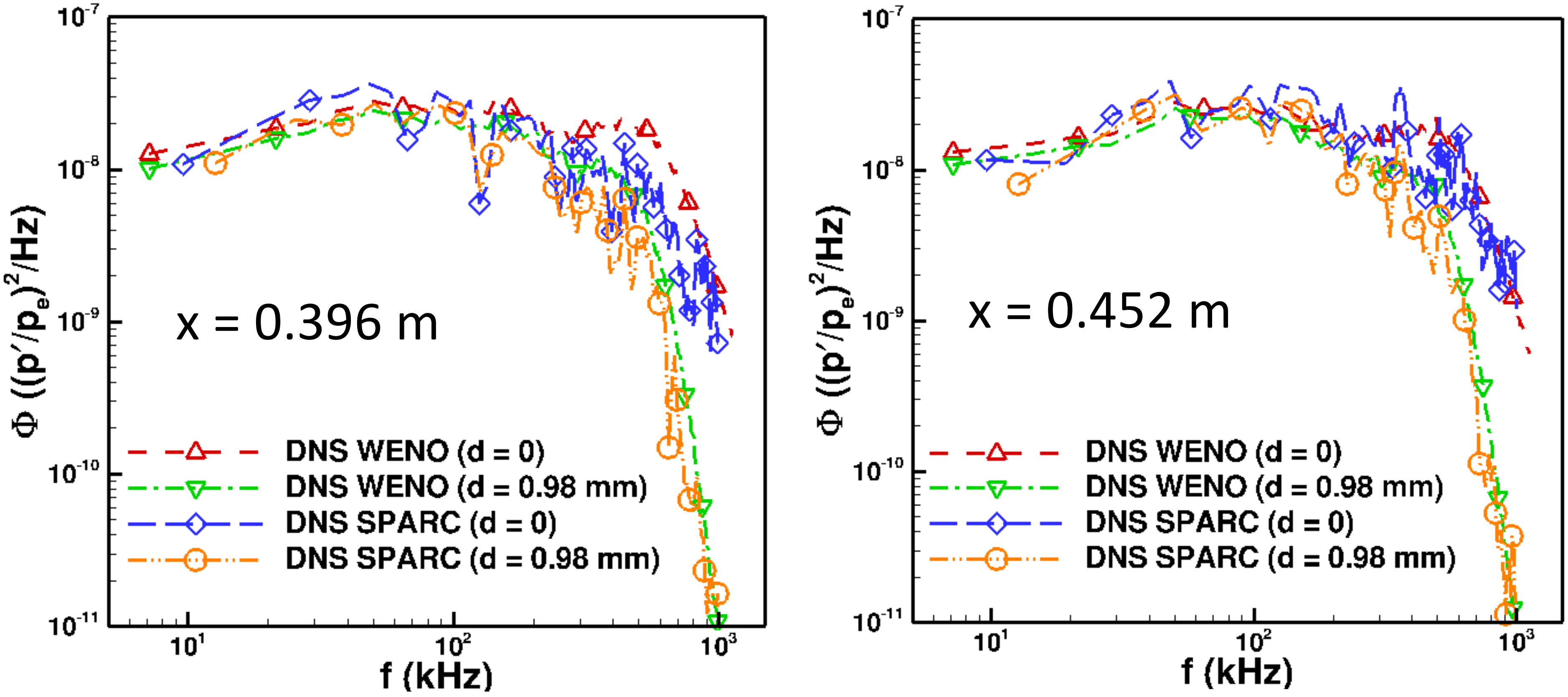
Assessment of Inflow BC and Flow Solvers

- p'_{rms}/p_w of WENO runs recovers from initial transient due to DF inflow after $L_{adjust} \cong 0.15$ m
- p'_{rms}/p_w prediction with the SPARC code shows a large initial peak due to the breakdown of second-mode waves
- p'_{rms}/p_w predicted by WENO and SPARC runs converge (within 10%) in the downstream portion of the computational box



DNS of Hypersonic Wind Tunnel Cone

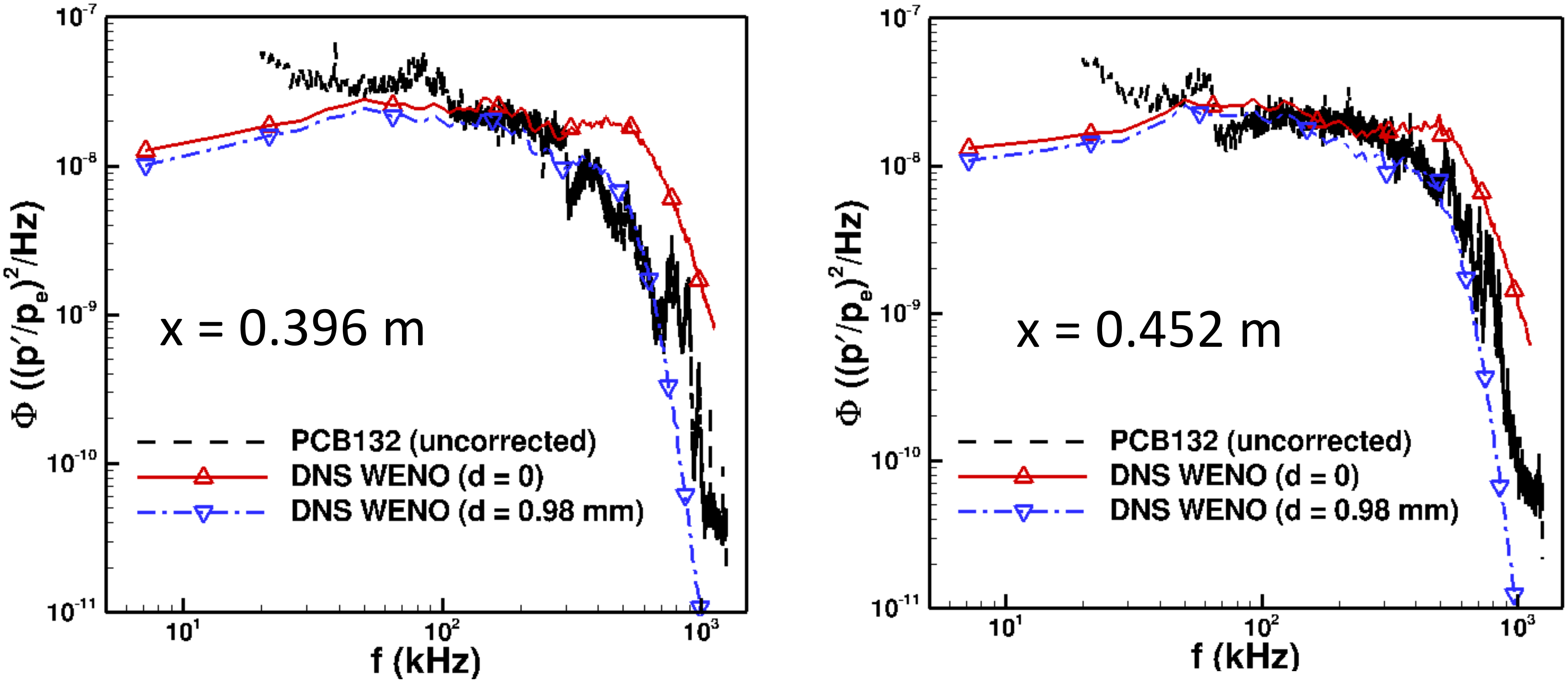
Assessment of DNS Data



- PSD computed from wall-pressure DNS field with and without spatial averaging
  - “raw” DNS data without spatial averaging (d = 0)
  - spatially-averaged DNS data over a circular area of diameter (d = 0.98 mm)
- PSD of p'_w predicted by WENO (with “Digital-Filtering” inflow) and SPRAC (with “BL transition” inflow)
  - compared well in the downstream portion of the computational box
  - confirmed the achievement of a fully developed equilibrium state of a turbulent boundary layer in selected DNS domain from $x \cong 0.4$ m

DNS of Hypersonic Wind Tunnel Cone

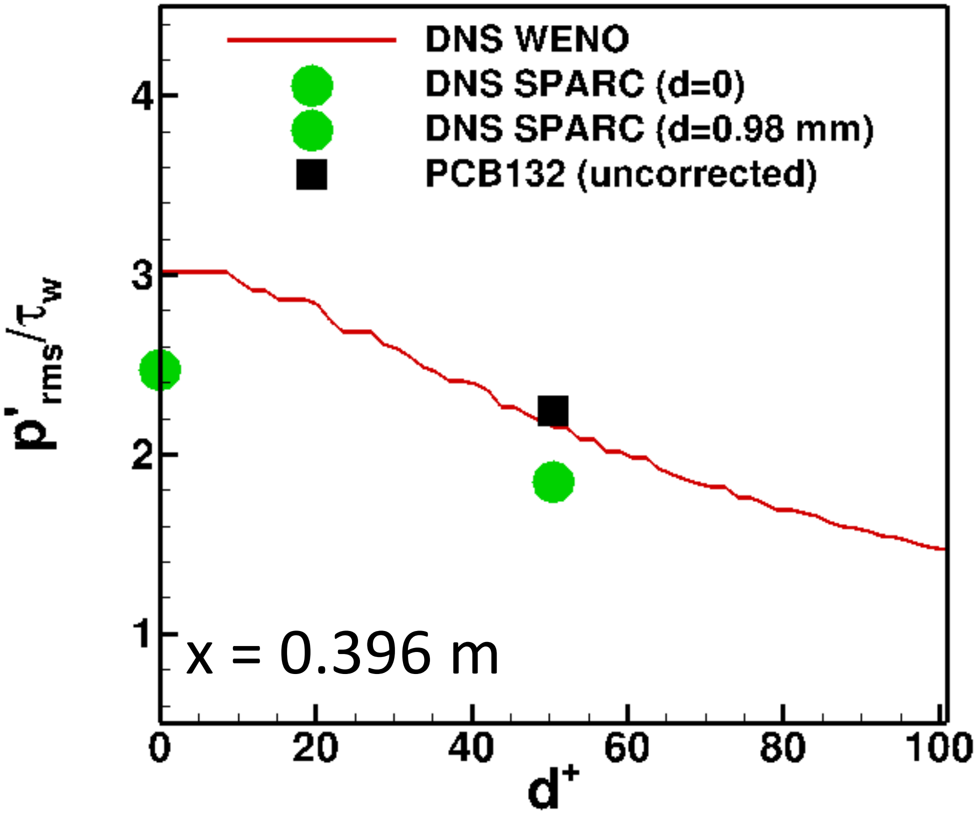
Comparison with Experiment

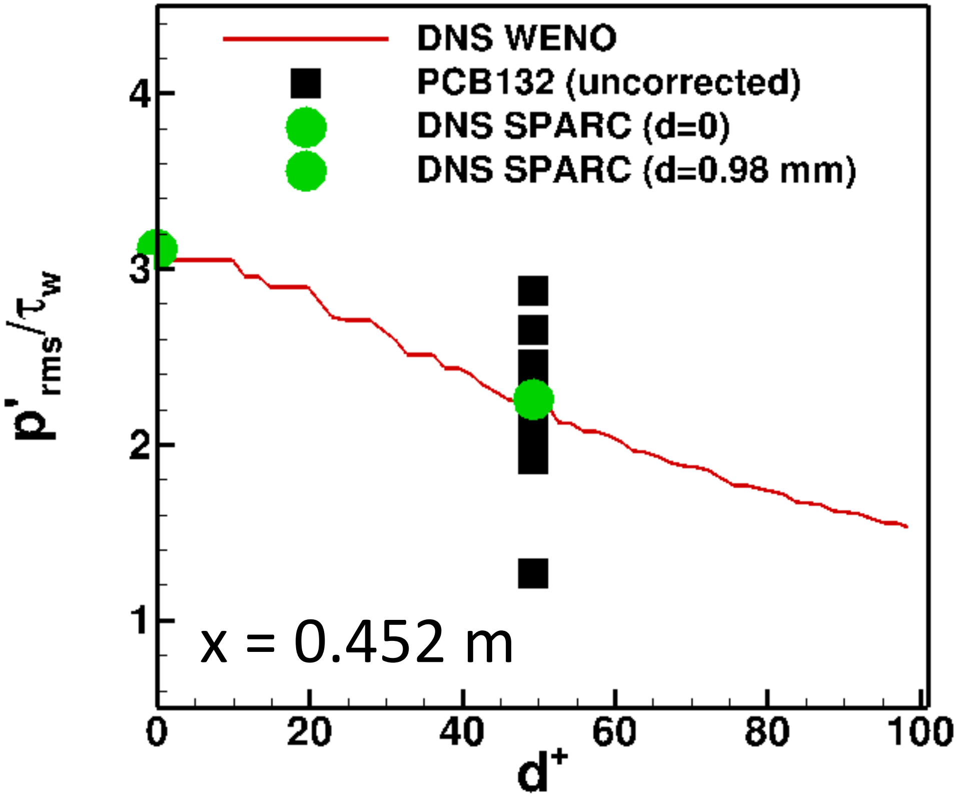


- Size of the PCB-132 transducer caused significant attenuation at high frequencies in the experimentally measured PSD
  - Diameter d = 0.98 mm (or d = 0.0386 inches) is the sensing area of the PCB132 transducer provided by PCB PIEZOTRONICS, Inc. (corresponding to $d^+ = 50$)
  - Faster spectral roll-off of experimentally measured PSD at high frequencies than those of the DNS without spatial averaging (d = 0)
  - Good comparison achieved between the experimentally measured PSD and the PSD computed from the spatially-averaged DNS data with d = 0.98 mm

DNS of Hypersonic Wind Tunnel Cone

Comparison with Experiment





- Attenuation of p'_{rms} resulting from the finite transducer size
  - Good comparison in p'_{rms} is achieved between DNS and experiments for an averaging diameter of d = 0.98 mm ($d^+ = 50$)
  - Spatial averaging with d = 0.98 mm caused an attenuation of approximately 27%

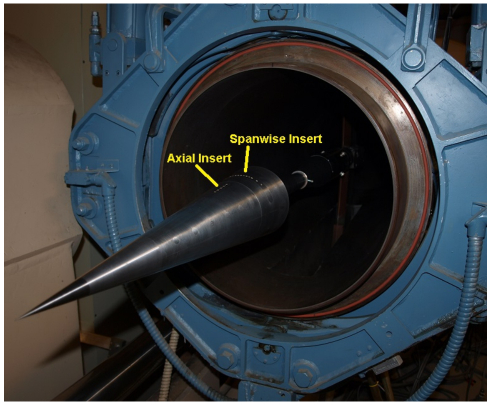
DNS of Hypersonic Wind Tunnel Cone

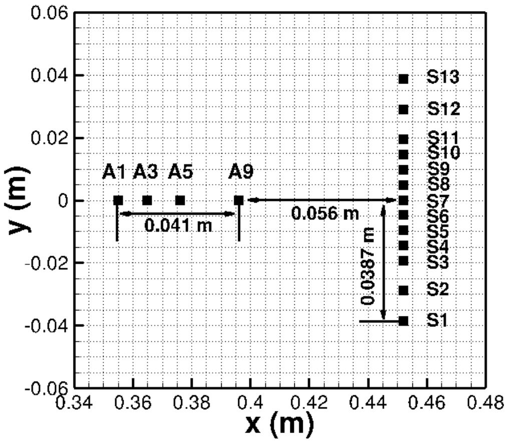
Comparison with Experiment

Coherence function

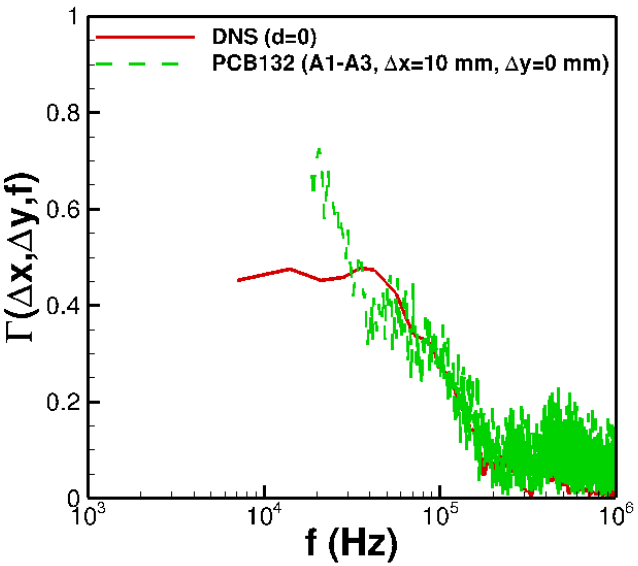
$$\Gamma^2(\Delta x, \Delta y, \omega) = \frac{|\Phi_{P_a P_b}(\Delta x, \Delta y, \omega)|^2}{|\Phi_{P_a P_a}(\omega)||\Phi_{P_b P_b}(\omega)|}$$

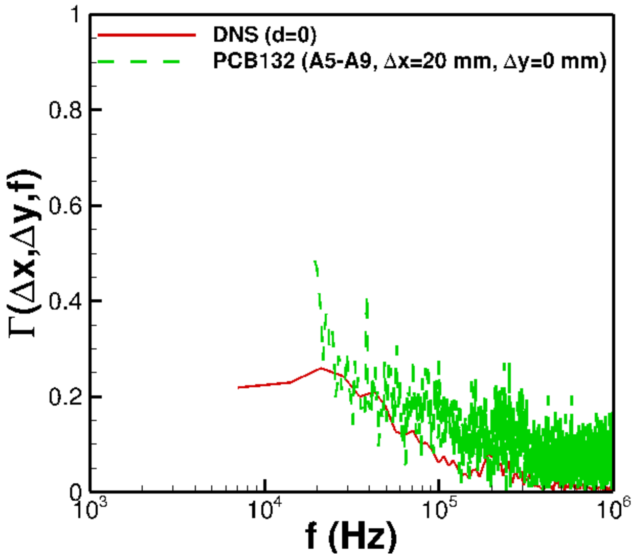
with $\Phi_{P_a P_b}(\Delta x, \Delta y, \omega)$ is the cross spectral density calculated as

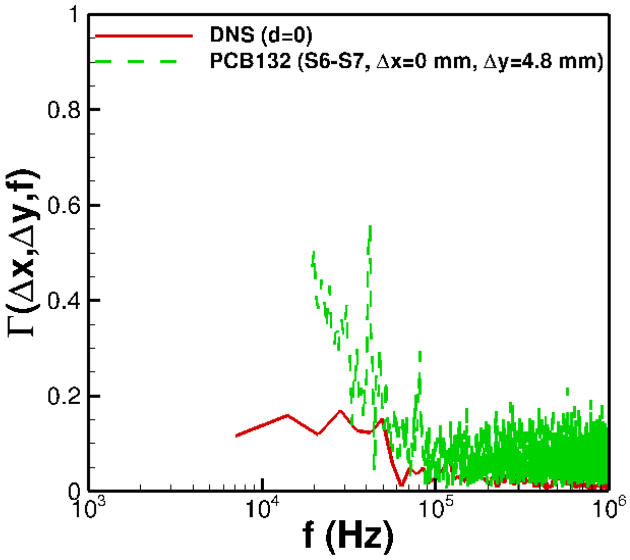




$$\Phi_{P_a P_b}(\Delta x, \Delta y, \omega) = \overline{\widetilde{p}^*(x, y, \omega), \widetilde{p}(x + \Delta x, y + \Delta y, \omega)}$$







- The DNS-predicted coherence compares well with that in experiments for transducers with either streamwise (Δx) or spanwise (Δy) separations
- Finite sensor size seems to have only a small influence on wall-pressure coherence

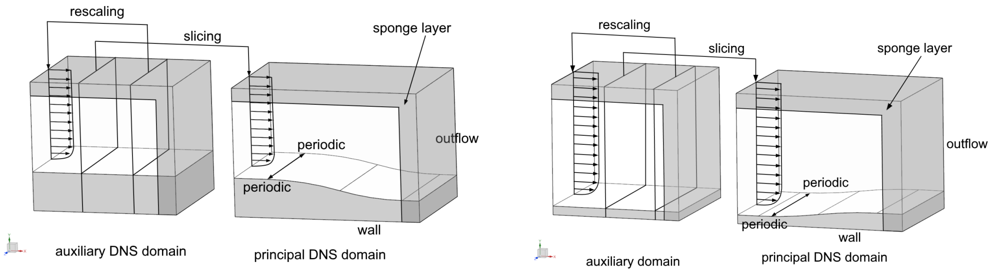
DNS of Hypersonic Wind Tunnel Cone

Summary

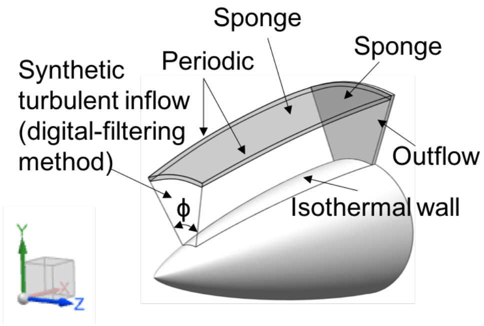
- DNS were conducted to characterize TBL over a sharp 7° half-angle cone at Mach 8 and Re/m = 13.4M
  - Cone geometry and flow conditions representative of Sandia HWT-8
  - Insensitivity of turbulence statistics to domain boundaries verified by performing multiple DNS runs with different extents of the axial domain and inflow boundary conditions
  - Good comparison achieved in wall-pressure spectrum and coherence between DNS and Sandia's experiments

- The cone DNS study laid foundation for follow-on DNS study of hypersonic TBLs over an axisymmetric ogive

Next Steps



- Extend the DNS database to include TBLs subject to pressure gradients
  - Canonical geometries
    - 2-D planar convex and concave walls
    - 2-D circular ogive
  - Validation of DNS against experiments at Texas A&M University (TAMU)



- Characterize hypersonic turbulence physics
  - Mean and turbulence statistics
  - Budgets of TKE and Reynolds-stress transport
  - Compressibility transformations

- Assess turbulence models
  - Reynolds-stress transport (RST) models
  - Algebraic energy flux (AEF) model by Bowersox

Acknowledgment

- Dr. Rodney Bowersox
  - for collaborative work on RANS model assessment
- Dr. Katya Casper
  - for providing experimental data for comparison with DNS
- Drs. Ross Wagnild and Neal Bitter
  - for their collaborative computational work of Sandia Cone
- Computational resources
  - DoD High Performance Computing Modernization Program
  - Ohio Supercomputer Center

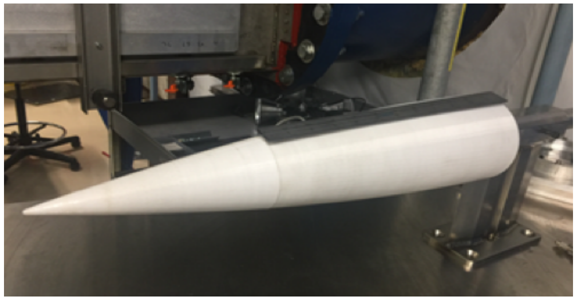
Publications

1. Huang, J., Nicholson, G. L., Duan, L., Choudhari, M. M., & Bowersox, R. D. (2020). “*Simulation and Modeling of Cold-Wall Hypersonic Turbulent Boundary Layers on Flat Plate*”. AIAA SciTech 2020 Forum, AIAA Paper 2020-0571. https://doi.org/10.2514/6.2020-0571
2. Huang, J., Duan, L., Casper, K. M., Wagnild, R., & Bitter, N. (2020). “*Direct Numerical Simulation of Turbulent Pressure Fluctuations over a Cone at Mach 8*”. AIAA SciTech 2020 Forum, Orlando, FL. AIAA Paper 2020-1065. https://doi.org/10.2514/6.2020-1065

Technical challenges remaining

- DNS of flow over a 2-D axisymmetric ogive
    - Selection of DNS inlet location relative to the tripping location in the experiment
    - Isolation of residual effects of boundary-layer trip on experimentally measured turbulence statistics
    - Determination of boundary-layer adjustment length caused by boundary-layer trip

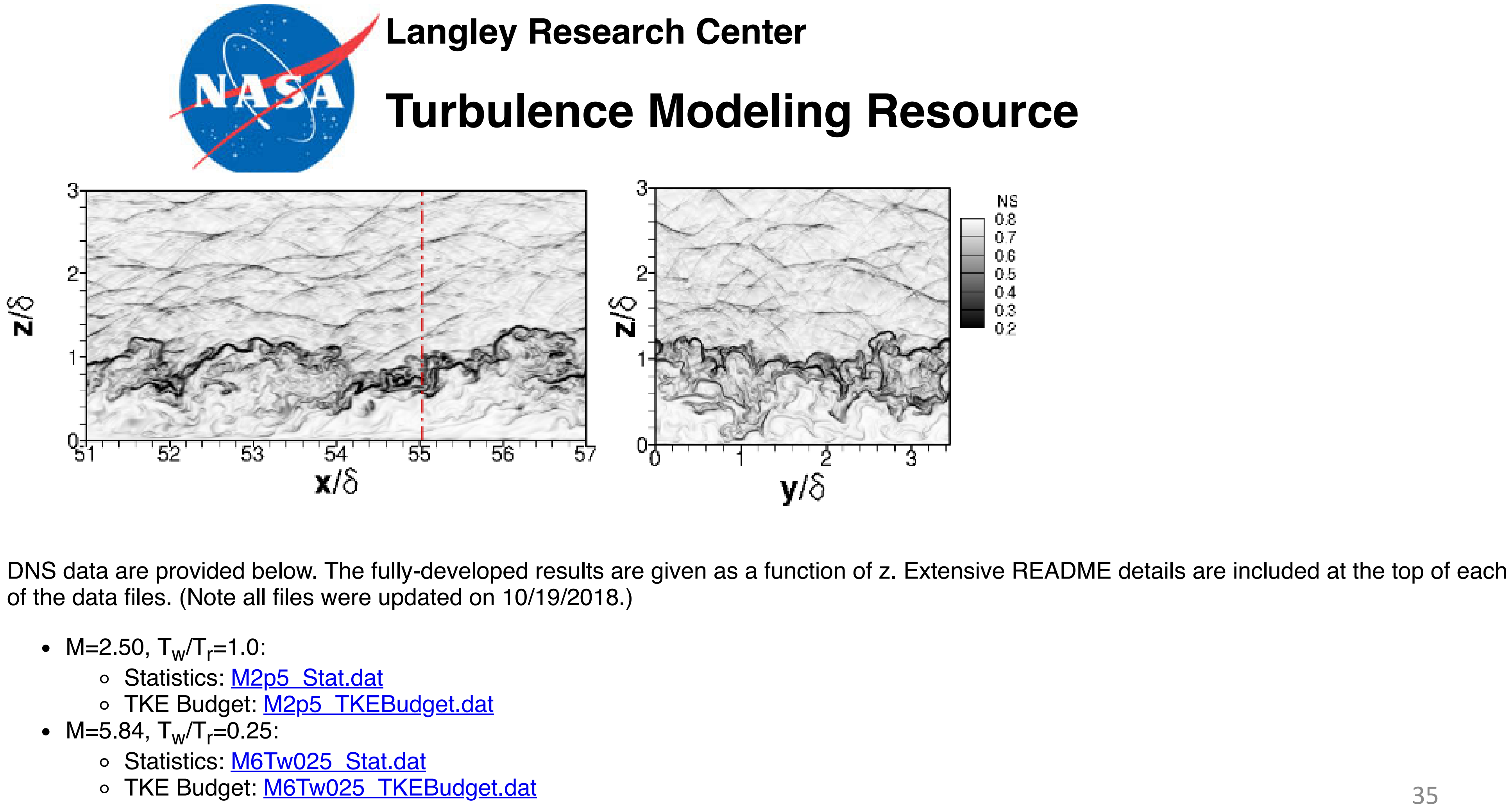
Ogive model tested by TAMU (courtesy: Prof. R. Bowersox)



Backup

Webpage of DNS Database

- DNS statistics (Mean BL profiles, Reynolds stresses, TKE budgets, etc.) posted on Turbulence Modeling Resource Website created by AIAA’s Turbulence Model Benchmarking Working Group
  https://turbmodels.larc.nasa.gov/Other_DNS_Data/supersonic_hypersonic_flatplate.html



Langley Research Center

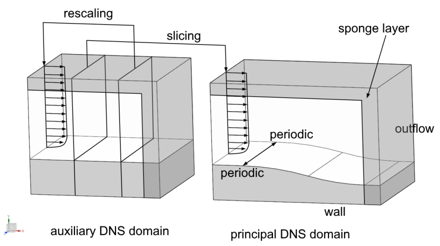
Turbulence Modeling Resource

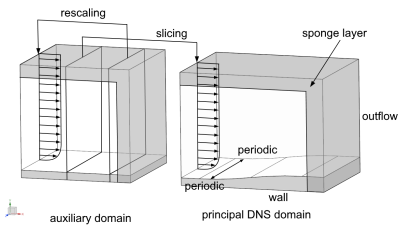
DNS data are provided below. The fully-developed results are given as a function of z. Extensive README details are included at the top of each of the data files. (Note all files were updated on 10/19/2018.)

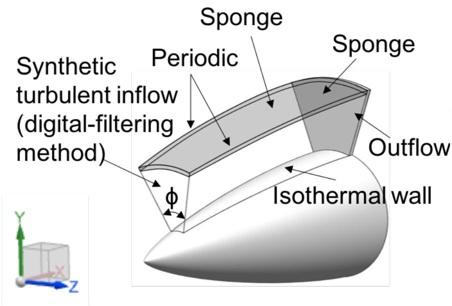
- M=2.50, T_w/T_r=1.0:
  - Statistics: M2p5_Stat.dat
  - TKE Budget: M2p5_TKEBudget.dat
- M=5.84, T_w/T_r=0.25:
  - Statistics: M6Tw025_Stat.dat
  - TKE Budget: M6Tw025_TKEBudget.dat

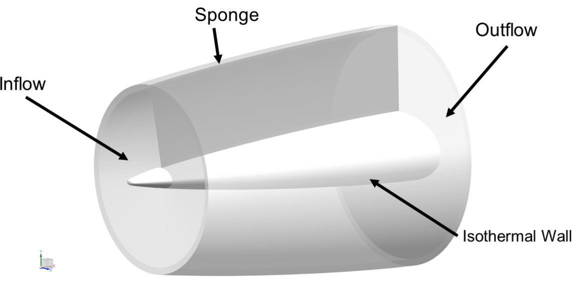
Next Steps

- Develop DNS database of hypersonic TBLs subject to **pressure gradient** and **wall cooling**
  - ❑ Canonical geometries
    - 2-D planar convex and concave walls
    - 2-D circular ogive
    - 3-D elliptic ogive









  - ❑ Adiabatic wall ($T_w/T_r = 1$) and cold wall ($T_w/T_r << 1$)
  - ❑ Validation of DNS against experiments at Texas A&M U.

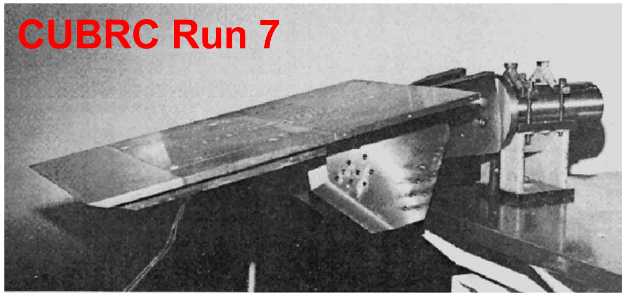
- Characterize boundary-layer turbulence
  - ❑ Mean and turbulence statistics
  - ❑ Budgets of TKE and Reynolds-stress transport
  - ❑ Compressibility transformations

- Collaborate with R. Bowersox's group to assess turbulence models
  - ❑ Reynolds-stress transport (RST) models
  - ❑ Turbulent heat flux model by Bowersox

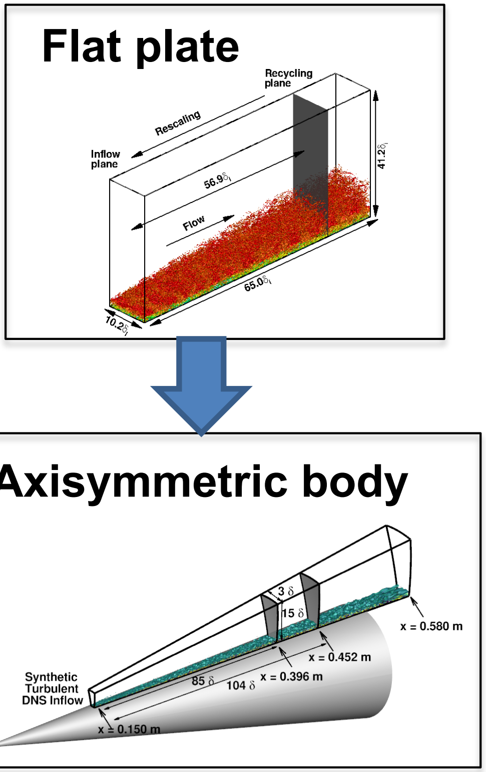
Summer of New Results

- Conducted DNS for a zero-pressure-gradient TBL at $M_\infty = 11.1$ on a highly-cooled flat plate (representative of CUBRC Run 7)
  - ☐ Extended the existing DNS database to a moderately higher Reynolds number ($Re_\tau \cong 1200$)
  - ☐ Studied hypersonic turbulence with strong wall cooling ($T_w/T_r = 0.2$)
  - ☐ Assessed Bowersox's algebraic energy flux (AEF) model using DNS data

- Simulated a TBL at $M_\infty = 8$ on a 7-deg half-angle circular cone
  - ☐ Established a procedure of conducting DNS for hypersonic TBLs over an axisymmetric hypersonic body
  - ☐ Laid a foundation for follow-on study of hypervelocity ogive cylinder of interest to ONR



Gnoffo, JSR 2013



Previous Work

- **DNS datasets of supersonic and hypersonic TBLs** (*Zhang et al. Vol. 56, No. 11, pp. 4297-4311, AIAAJ, 2018*)
  - ❑ Flow conditions representative of several hypersonic wind tunnels
    - Purdue Quiet Tunnel at Mach 6, Sandia Hypersonic Wind Tunnel at Mach 8, AEDC Tunnel 9 at Mach 14
    - Allow for one-to-one comparisons with wind-tunnel experiments
  - ❑ Based on a high-order scheme with a large domain size and sufficiently long sampling size ($L_x/\delta_i > 50$, $L_y/\delta_i > 8$, $T_f u_\tau/\delta_i > 5$) to
    - minimize any artificial effects due to inflow turbulence generation
    - ensure the convergence of selected high-order turbulence statistics