2017 University Turbine Systems Research Workshop
1-3 November 2016

RANS and LES of Internal and Film Cooling

Tom I-P. Shih, Kenny Hu, and Zach Stratton
School of Aeronautics and Astronautics, Purdue University

Mark Bryden
Ames National Laboratory, U.S. Dept. of Energy

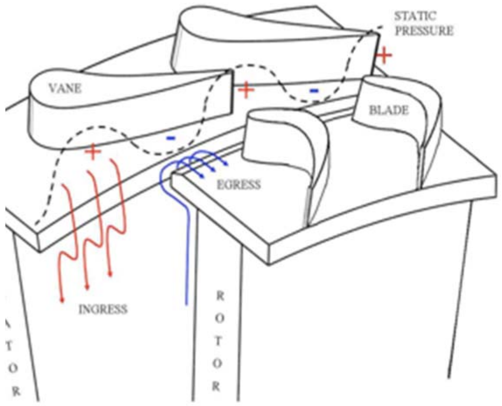
Robin Ames and Rich Dennis
National Energy Technology Laboratory, U.S. Dept. of Energy

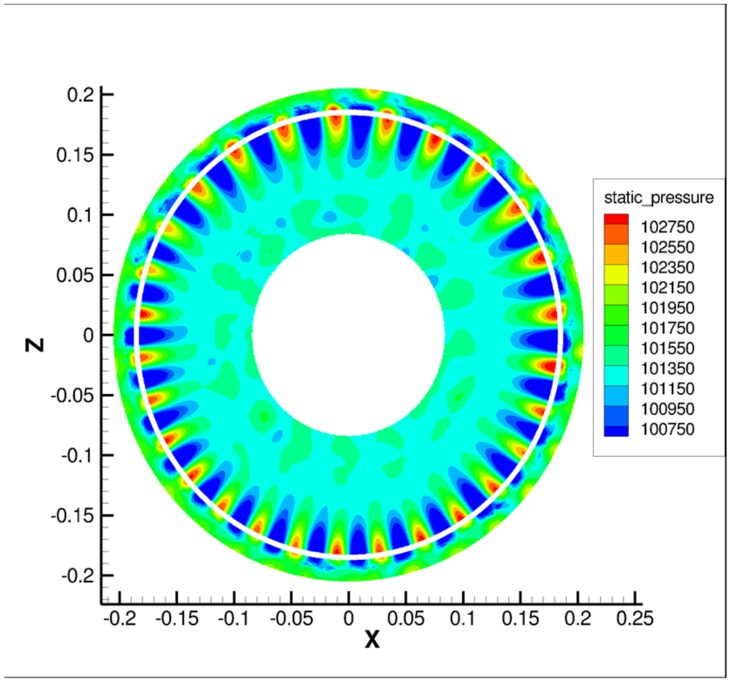
DoE – NETL & Ames Laboratory

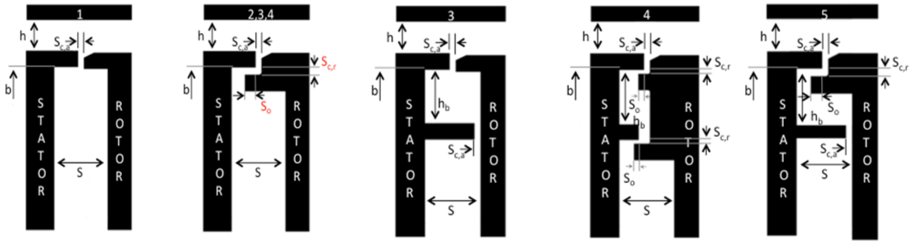
Our research group focuses on GT heat transfer.

Current efforts:

- **Develop & Assess Rim Seals:**
  3 papers submitted to 2018 IGTI
  - **LES** (360° with all vanes & blades) to understand flow physics.
  - **Steady & unsteady RANS** to study of seal designs for rotationally-induced ingress.
  - **Reduced-order modeling** of rotationally induced ingress.





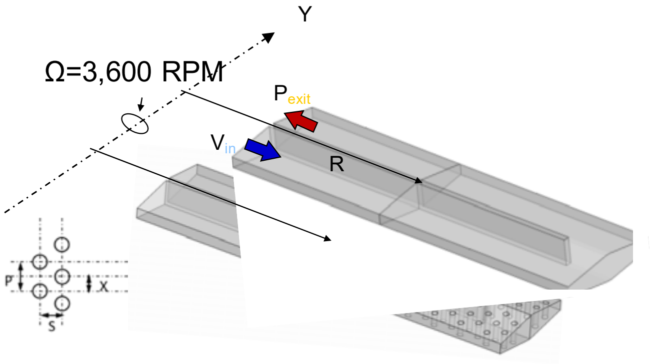


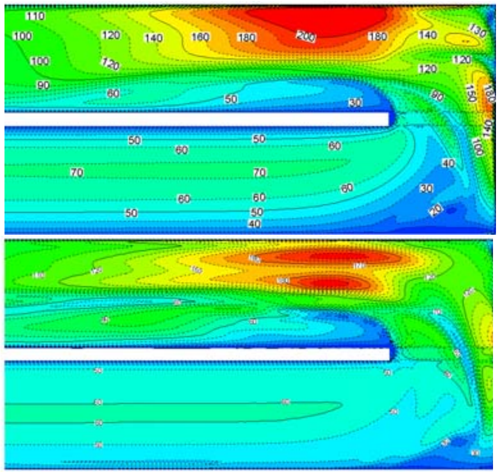
DoE – NETL & Ames Laboratory

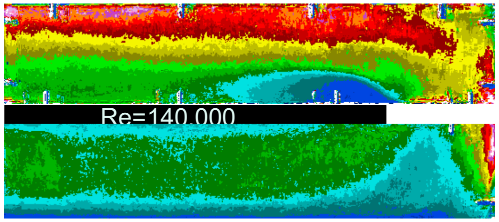
Our research group focuses on GT heat transfer.

Current efforts:

- **Develop & Assess Rim Seals:** 3 papers submitted to 2018 IGTI
- **Physics-Based Modelling & Simulation for Turbine Cooling:** 3 papers submitted to 2018 IGTI
  - **Steady and steady RANS + LES** of internal cooling in a U-duct with trapezoidal cross section.
  - **Unsteady RANS & LES** for film cooling.
  - **BC for LES and BC** at the interface between RANS and LES for hybrid methods.
  - **AI/machine learning** to guide RANS modeling from LES data.







DoE – NETL & Ames Laboratory

Our research group focuses on GT heat transfer.

Current efforts:

- **Develop & Assess Rim Seals:** 3 papers submitted to 2018 IGTI
- **Physics-Based Modelling & Simulation for Turbine Cooling:** 3 papers submitted to 2018 IGTI

- **Examine Fundamental Issues** in Computing & Measuring Heat Transfer Relevant to GT Heat Transfer
  - **Scaling of data measured in the lab** (near 1 atm & room T) **to engine conditions** (high T & P).
  - **Scaling design of experiments** to assess cooling designs in protecting the turbine material with internal and film cooling as well as conjugate heat transfer.
  - Reduced-order design and analysis tools for higher fidelity preliminary design at the systems level.

Outline of Talk

- Current Efforts
- RANS and LES of Internal Cooling in a U-Duct with Trapezoidal Cross Section: Kenny Hu
- RANS and LES of Film Cooling: Zach Stratton

RANS and LES of Internal Cooling in a U-Duct with Trapezoidal Cross Section: Kenny Hu & Tom Shih

- Objective
- **Problem Description**
- **Formulation**
- **Numerical Method**
- **Results**
- **Summary**

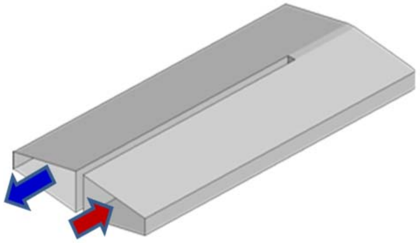
Objective

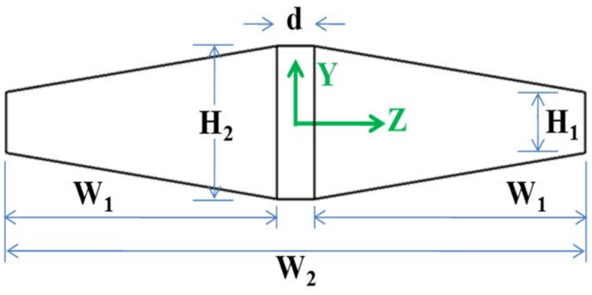
Provide ***benchmark LES data*** that can be used to assess turbulence models in RANS simulations with focus on heat transfer in a U-duct with trapezoidal cross-section.

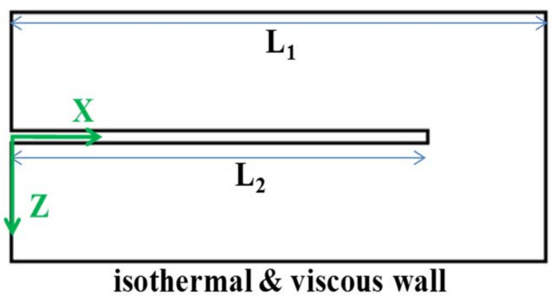
Perform ***RANS and LES to understand limitations of RANS models.***

Problem Description: Experimental

Experimental Setup: Dr. M. Chu, U. of Pittsburgh

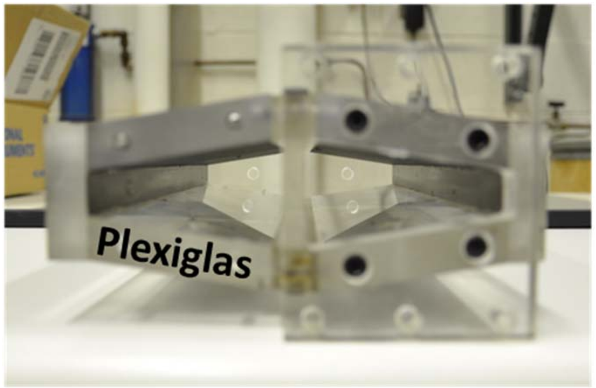


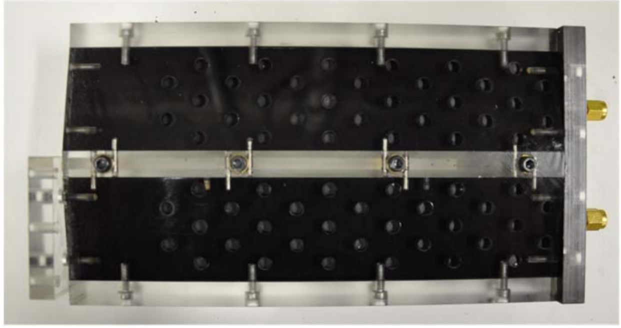


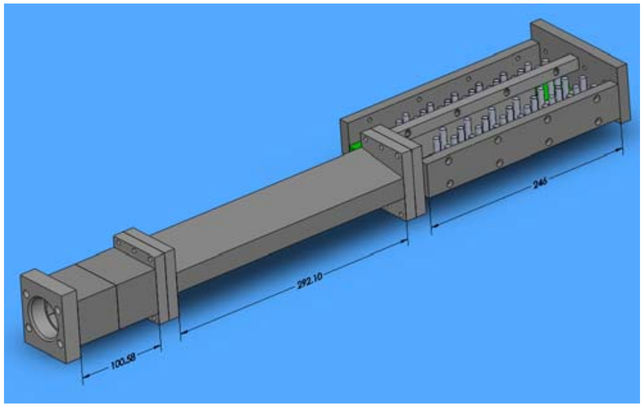


Unit: mm
D_h = 29.04
d = 6.35
L_1 = 246
L_2 = 192
W_1 = 54.24
W_2 = 114.83
H_1 = 11.72
H_2 = 28.48

Re = 20,000
V_{in} = 12.65 m/s
T_{in} = 343.15 K
T_{wall} = 313.15 K
P_{exit} = 101325 Pa



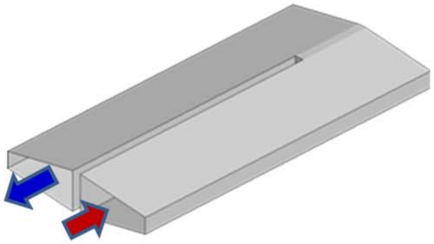


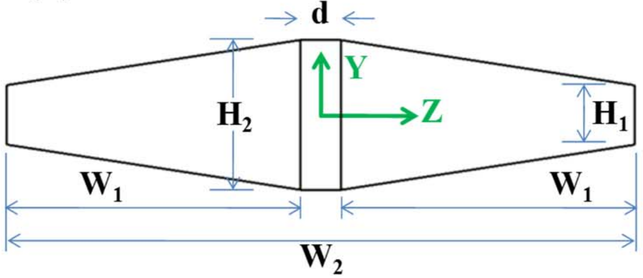


- Hot gas temperature at inlet = 70 ^{o}C.
- Initial wall temperature = 25 ^{o}C.
- Average wall T over duration of experiment is 40 ^{o}C.
- Nominal operating pressure is 1 atm.
- Re = 20,000 in test section.

Problem Description: CFD

(a)RANS:

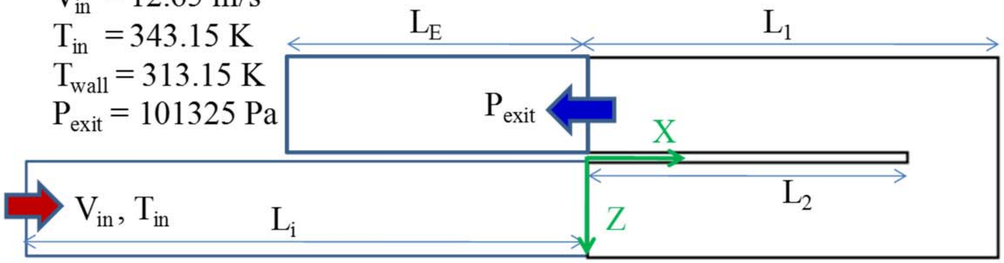




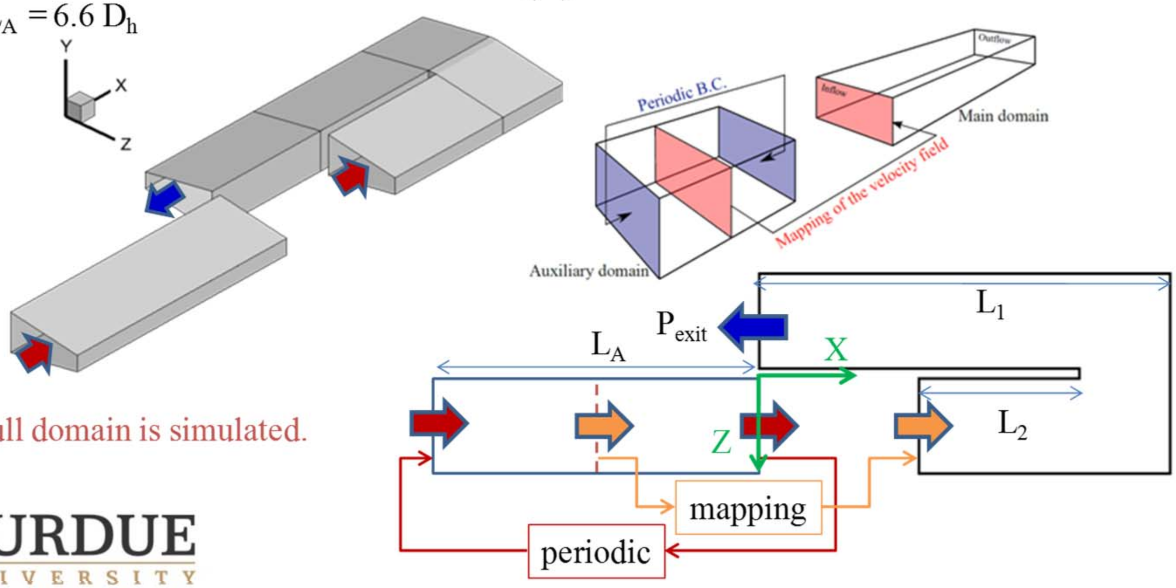
Only half of the domain is simulated.

Unit: mm
D_h = 29.04
d = 6.35
L_1 = 246
L_2 = 192
W_1 = 54.24
W_2 = 114.83
H_1 = 11.72
H_2 = 28.48
L_i = 40D_h
L_E = 384
L_A = 6.6 D_h

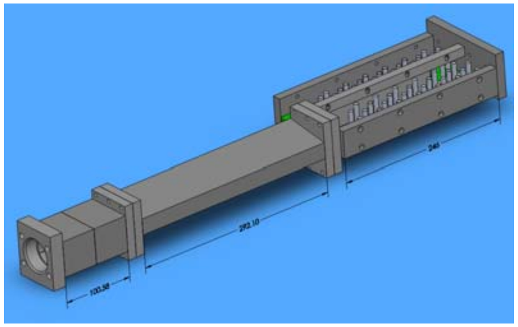
Re = 20,000
V_{in} = 12.65 m/s
T_{in} = 343.15 K
T_{wall} = 313.15 K
P_{exit} = 101325 Pa



(b)LES:



Full domain is simulated.



RANS: extension ducts added to get
- fully developed flow at U-duct inlet
- no reverse flow at duct exit

LES:
- U-duct's upleg shortened to reduce computational cost.
- Upstream straight duct w/ same cross section & flow conditions is used to **generate inflow BC for LES**.

Formulation: Governing Equations

Assumptions:

Incompressible flow with constant properties.

Air properties are calculated based on T = #*T_{inlet} + T_{wall})/2 = 328.15 K.

Thus, ρ = 1.0753 kg/m3, Cp = 1007 J/kg-K, k = 0.028332 W/m-K, μ = 1.9765X10^{-5} kg/m-s

RANS

Ensemble-averaged continuity, N-S, energy

Realizable k-ε Model

SST Model

Stress-Omega Reynolds Stress Models (RSM-τω)

LES

spatially filter continuity, N-S, and energy

WALE SGS Model:

$$\nu_{sgs} = (C_w \Delta)^2 \frac{\left(S^d_{ij} S^d_{ij}\right)^{3/2}}{\left(\hat{S}_{ij}\hat{S}_{ij}\right)^{5/2} - \left(S^d_{ij} S^d_{ij}\right)^{5/4}}$$

$$S^d_{ij} = \hat{S}_{ik}\hat{S}_{kj} + \hat{\Omega}_{ik}\hat{\Omega}_{kj} - \frac{1}{3}\left(\hat{S}_{mn}\hat{S}_{mn} - \hat{\Omega}_{mn}\hat{\Omega}_{mn}\right)\delta_{ij}$$

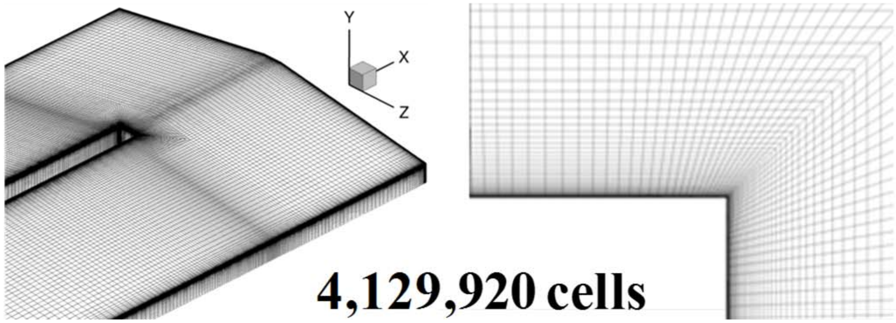
$$\overline{u_i' T'} = -\Gamma_t \frac{\partial T}{\partial x_i} \qquad \Gamma_{t,RANS} = \frac{\mu_t}{\mathrm{Pr}_t}$$

$$\frac{\partial \tau_{ij}}{\partial t} + \underbrace{\bar{u}_k \frac{\partial \tau_{ij}}{\partial x_k}}_{Convection(C_{ij}} = \underbrace{-\tau_{ik}\frac{\partial \bar{u}_j}{\partial x_k} - \tau_{jk}\frac{\partial \bar{u}_i}{\partial x_k}}_{Production(P_{ij})} + \boxed{\underbrace{2\nu \overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_j'}{\partial x_k}}}_{Dissipation\,(\varepsilon_{ij})}} + \boxed{\underbrace{\overline{\frac{p'}{\rho}\left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i}\right)}}_{Pressure-Strain\,(\Pi_{ij})}} + \underbrace{\frac{\partial}{\partial x_k}\left(\underbrace{\nu \frac{\partial \tau_{ij}}{\partial x_k}}_{Viscous} + \boxed{\underbrace{\overline{u_i' u_j' u_k'} + \frac{\overline{p' u_i'}}{\rho}\delta_{jk} + \frac{\overline{p' u_j'}}{\rho}}_{turbulent\,(D_{T,ij})}}\right)}_{Transport\ by\ Diffusion}$$

Grid System

RANS

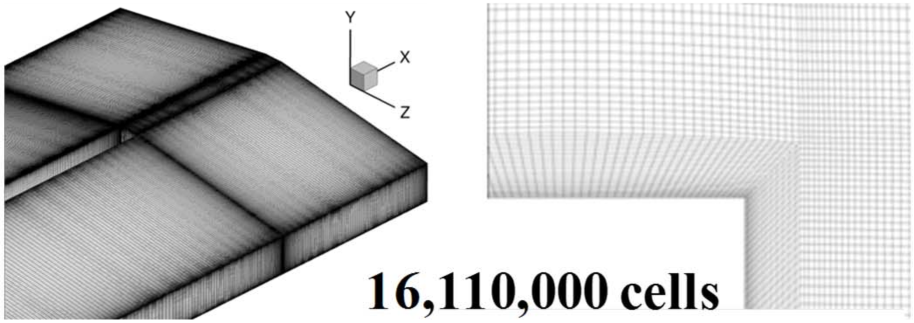
O-grid wrap around INNER wall



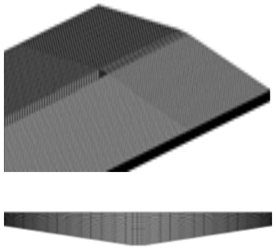
4,129,920 cells

LES

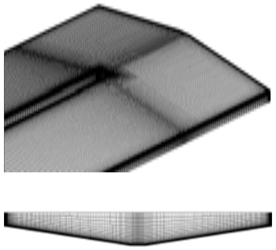
O-grid wrap around ALL the walls



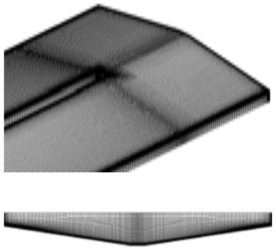
16,110,000 cells



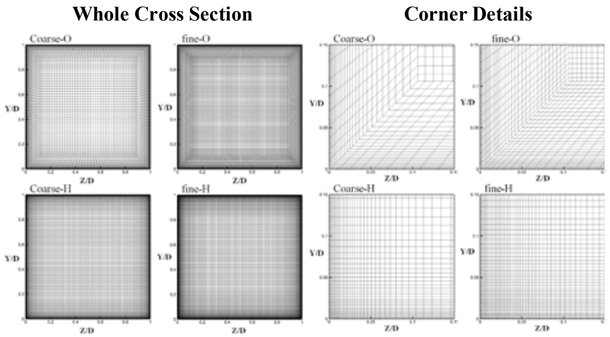
2,530,560 cells
for half domain

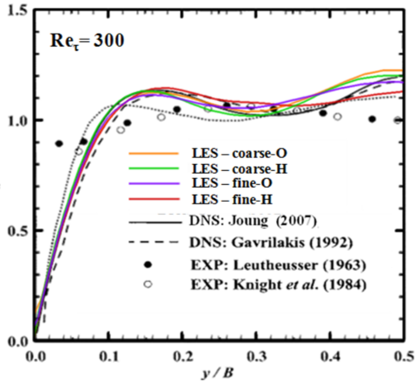


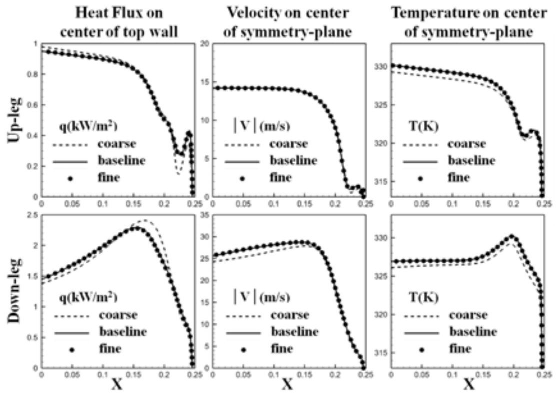
3,694,080 cells
for half domain



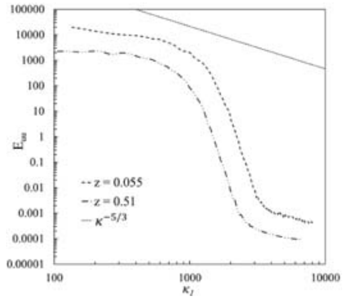
4,129,920 cells
for half domain



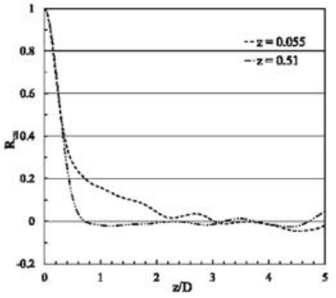


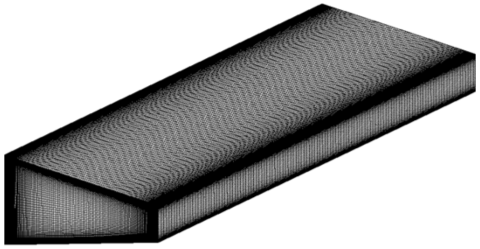


$$E(k) = C_1 \varepsilon^{2/3} k^{-5/3}$$



$$R_{uu} = \frac{\overline{u'(0,t)u'(X/D,t)}}{\overline{u'^2(0,t)}}$$



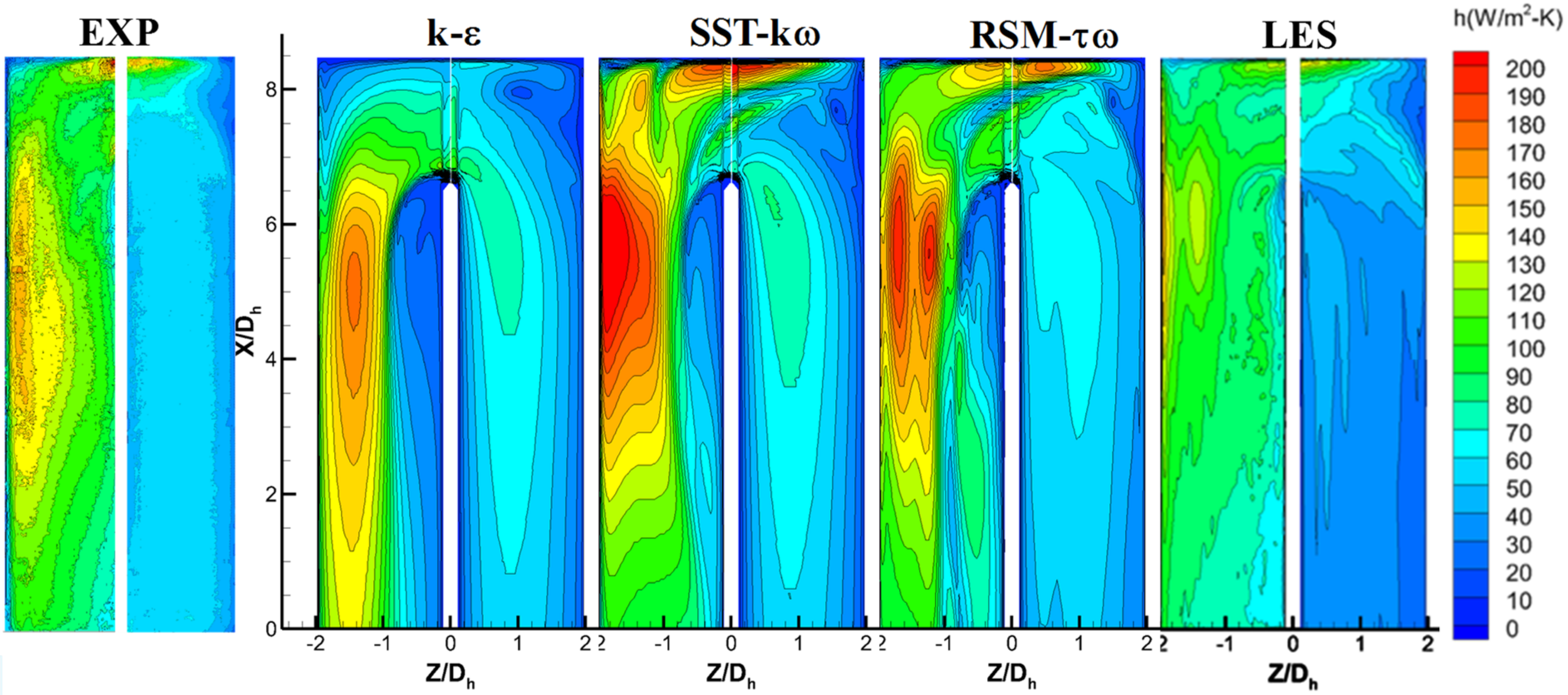


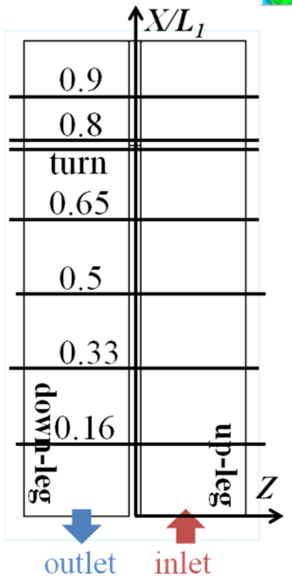
RANS and LES of Internal Cooling in a U-Duct with Trapezoidal Cross Section: Kenny Hu & Tom Shih

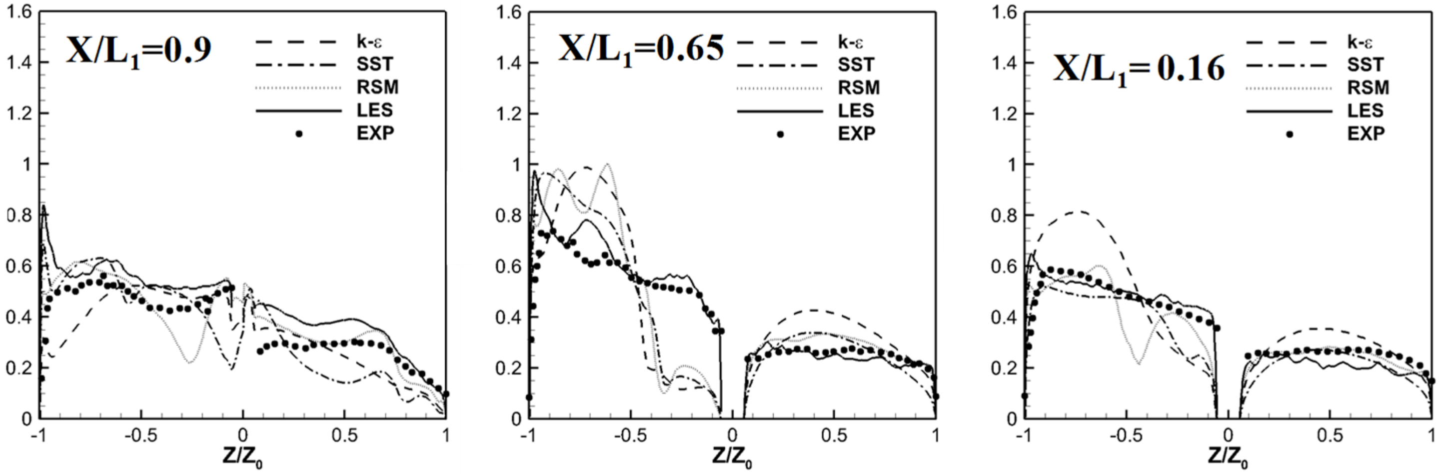
- **Objective**
- **Problem Description**
- **Formulation**
- **Numerical Method**
- **Results**
  - HTC : RANS vs. LES vs. EXP
  - Recirculation Bubble and Reattachment: RANS vs. LES
  - TKE, Eddy Viscosity, Reynolds Stresses: RANS vs. LES
  - Budget Terms: RSM vs. LES
  - EDH: RANS vs. LES
- **Summary**

Results: HTC

h/h_0

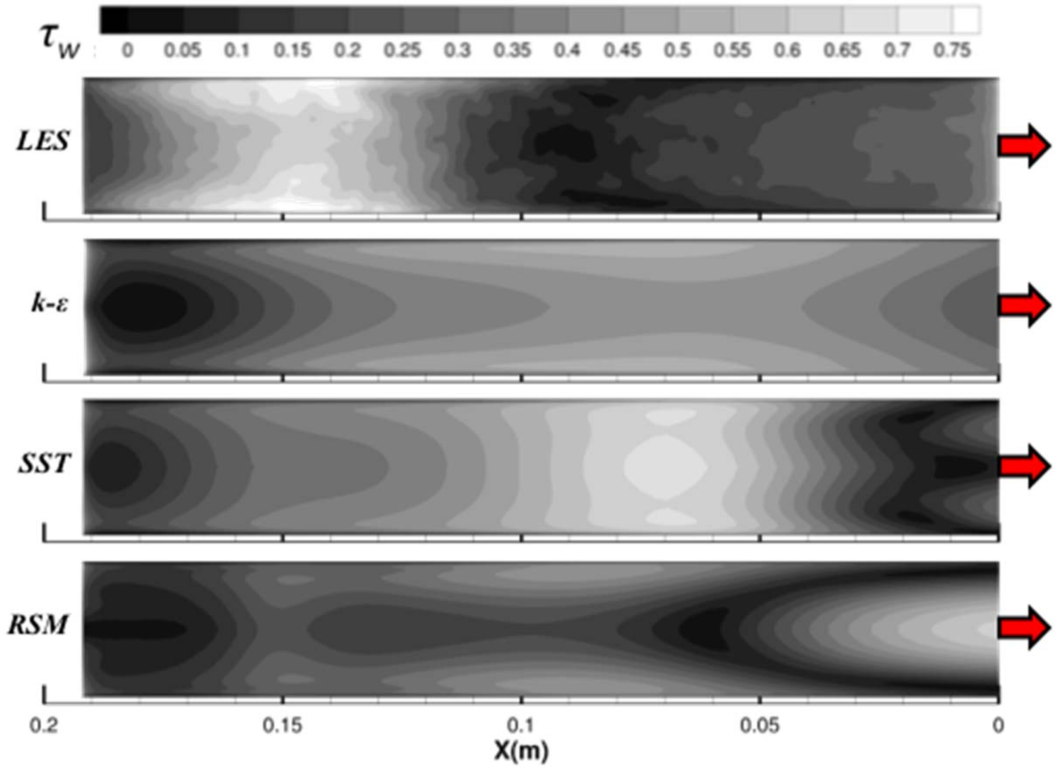


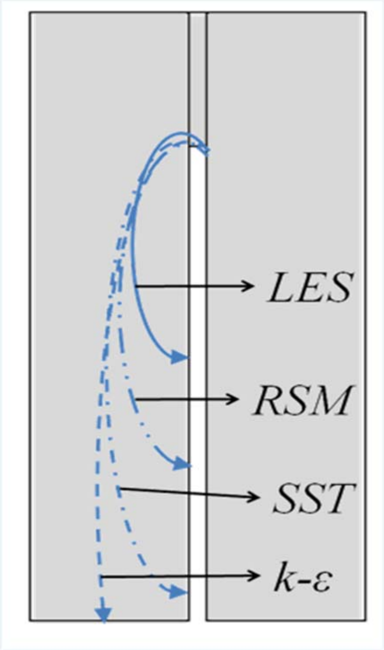




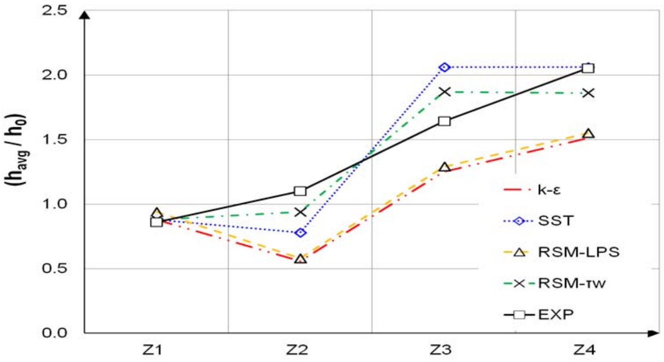
PURDUE
UNIVERSITY

Separation bubble and Reattachment#*RANS vs. LES)



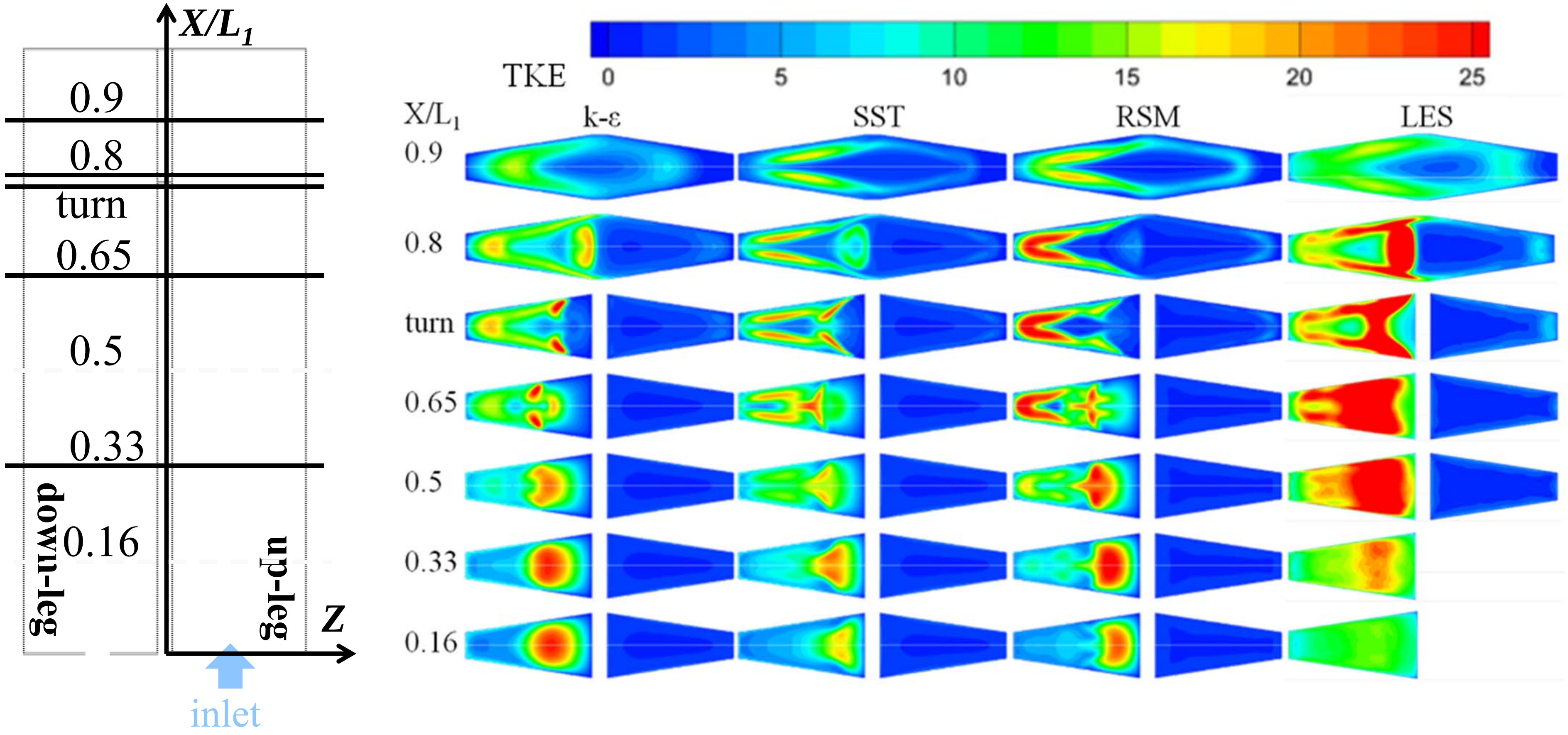


LES
showed the separation bubble is unstable and constantly sheds.

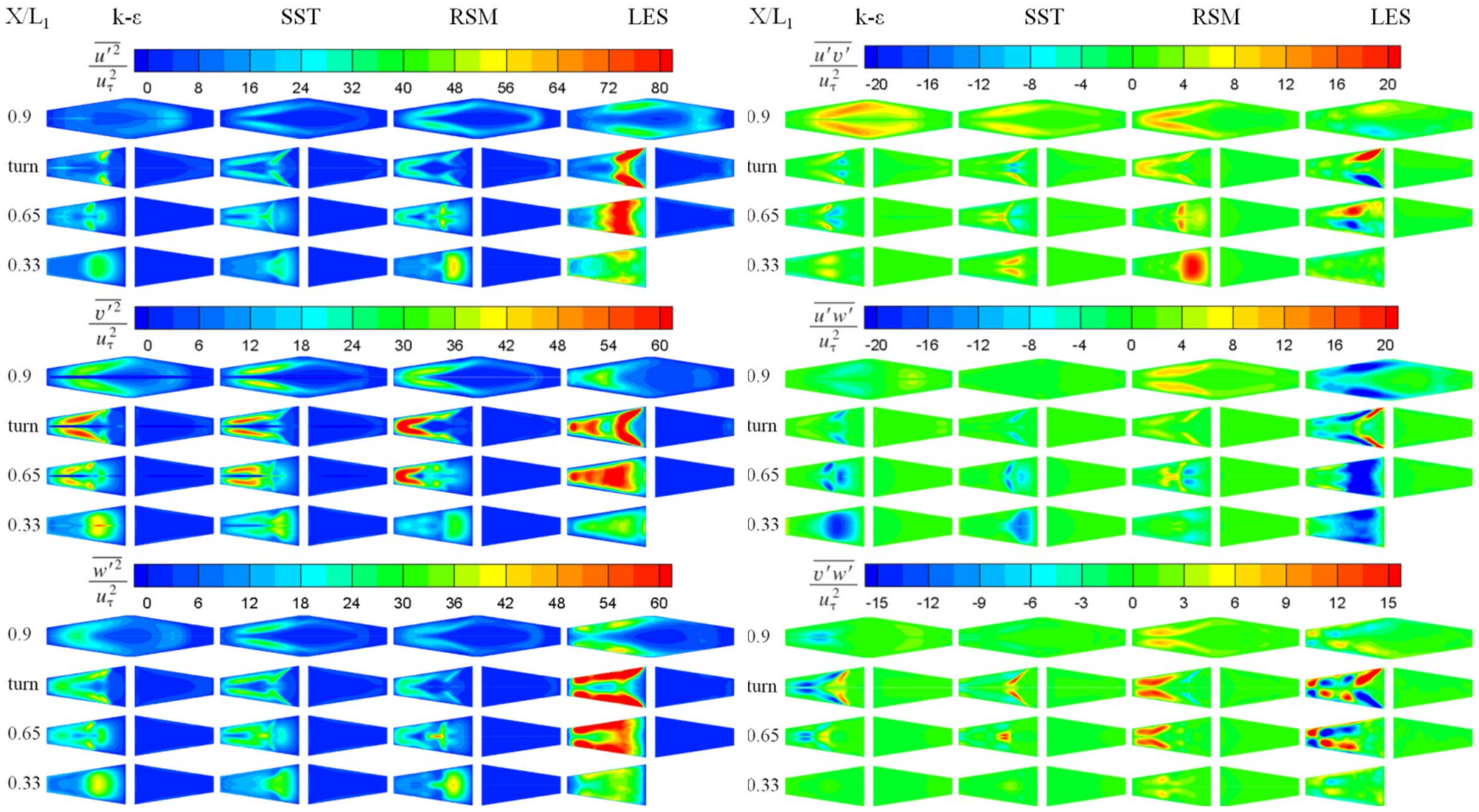


Though RANS predicts HTC distributions wrong, its predictions of the average HTC is not so bad.

TKE *RANS vs. LES)



Reynolds Stresses *RANS vs. LES)



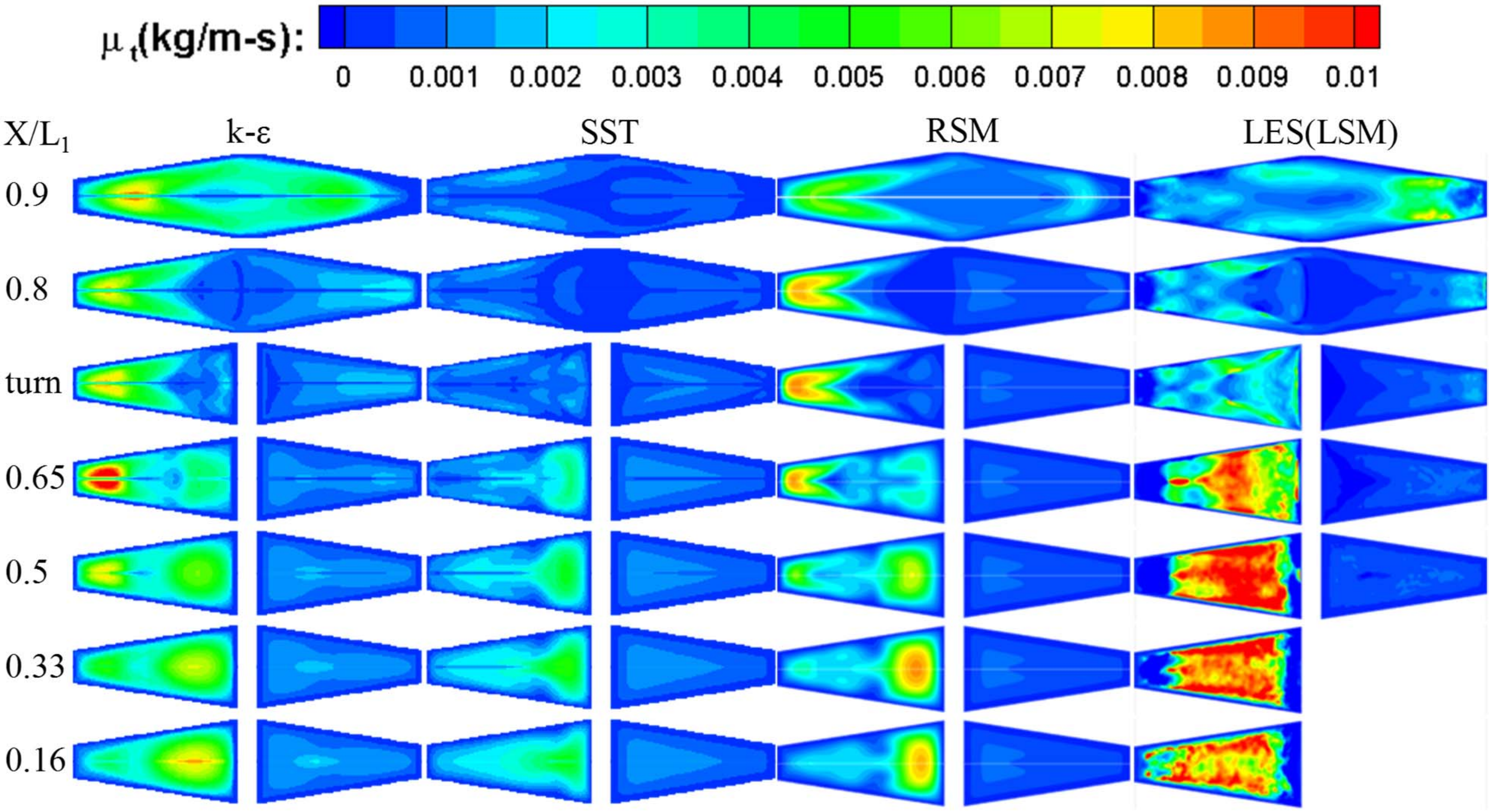
DoE – NETL & Ames Laboratory

Turbulent Viscosity (RANS vs. LES)

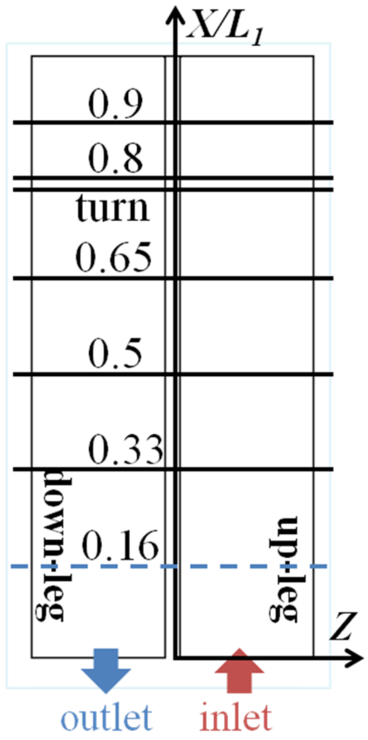
$$\textit{k-}\varepsilon:\ \mu_t^{k-\varepsilon} = \rho C_\mu \frac{k^2}{\varepsilon}$$

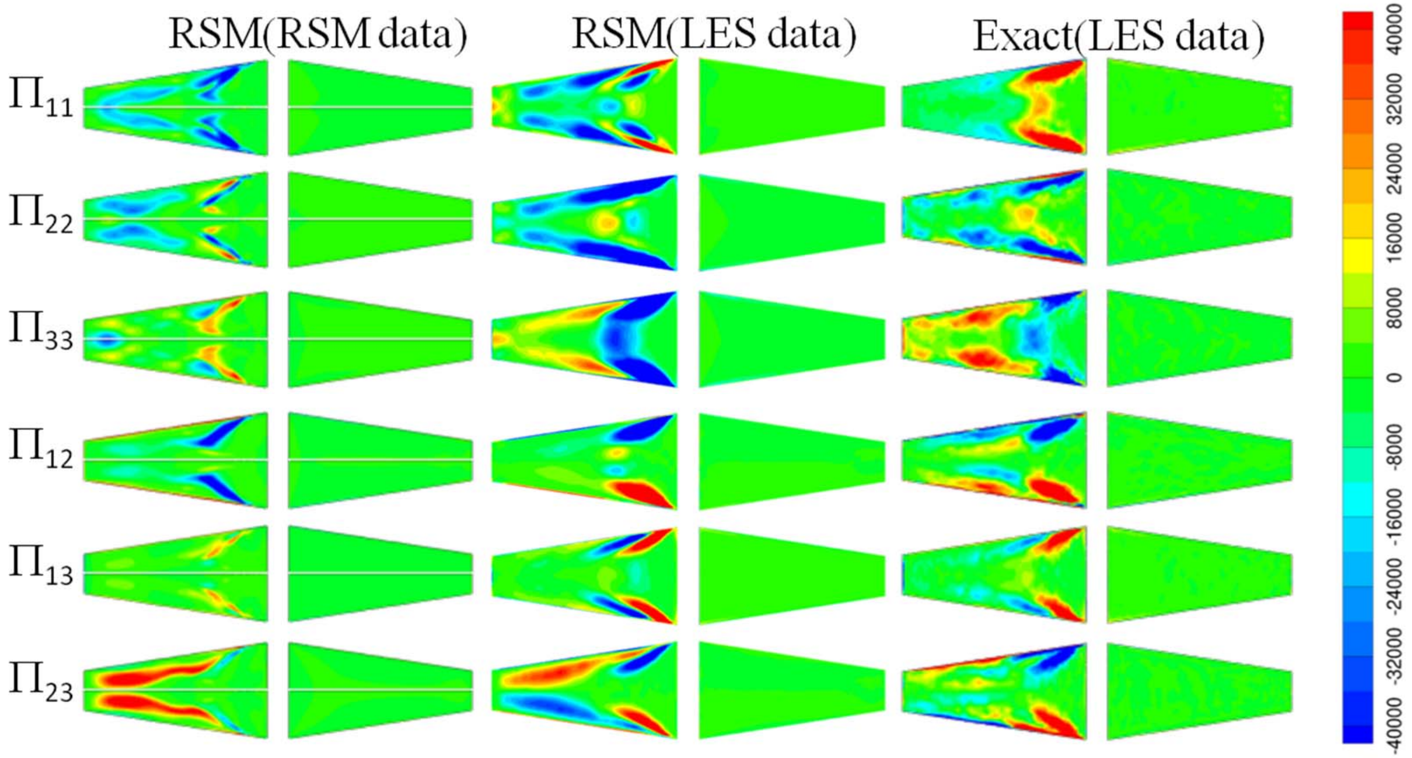
$$\textit{SST}\ \mu_t^{SST} = \rho \frac{k^2}{\omega}\left(\max\left[1, \frac{SF_2}{a_1\omega}\right]\right)^{-1} :$$

$$\textit{LES}:\quad \mu_t^{LES} = \rho \frac{-\overline{u_i' u_j'} S_{ij} + \frac{2}{3} k \delta_{ij} S_{ij}}{2 S_{kl} S_{kl}}$$

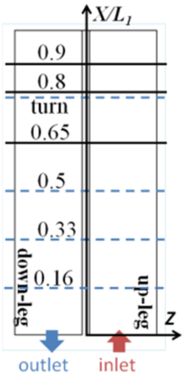


Pressure Strain Rate on X/L_1= Turn (RSM vs. LES)

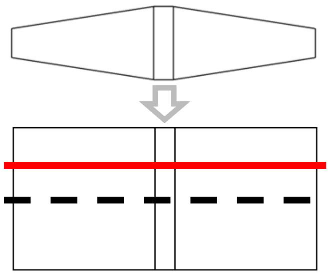


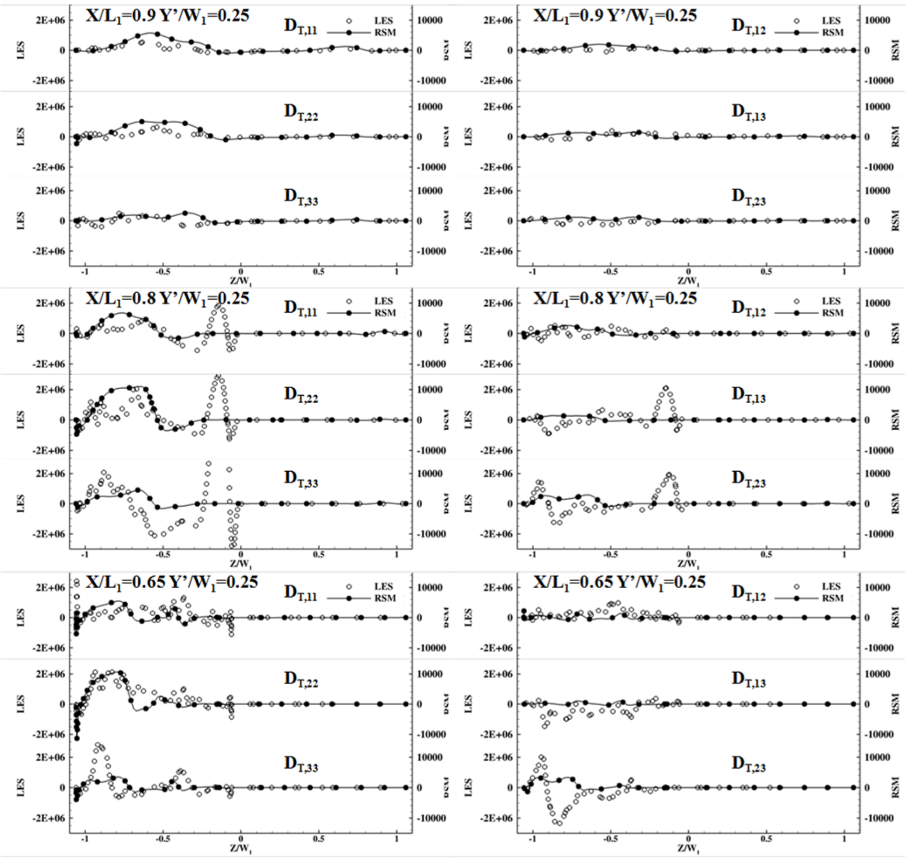


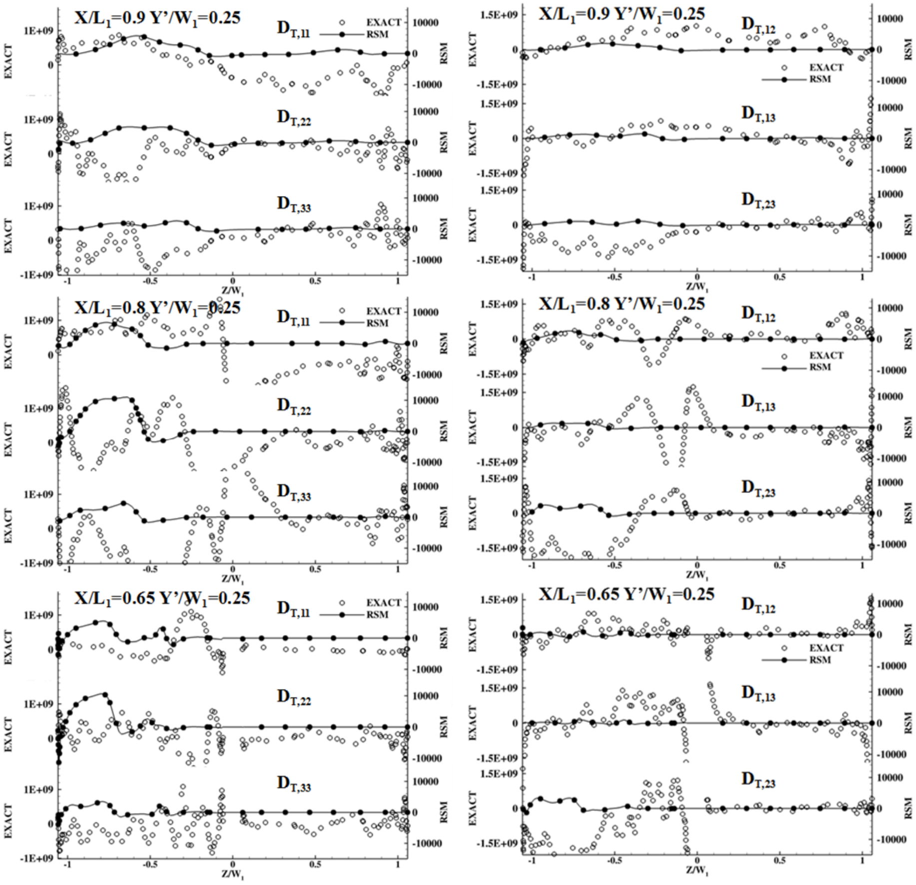
Turbulent Diffusion (RSM vs. LES)



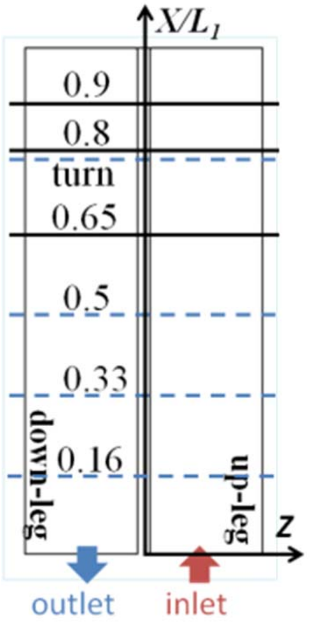
Mapping trapezoidal duct to square duct with the length of a side= W_1

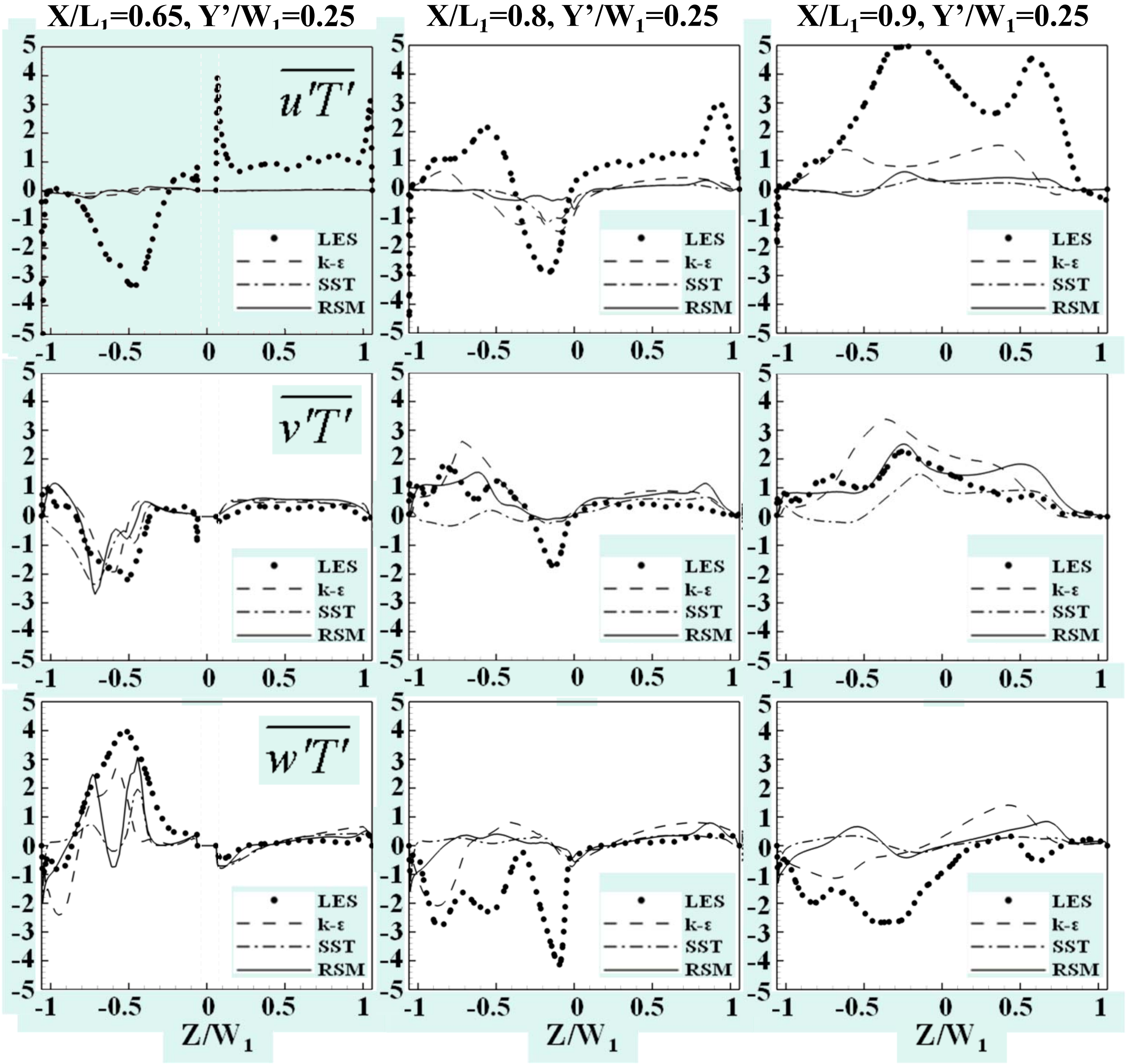


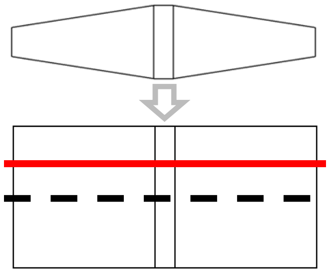




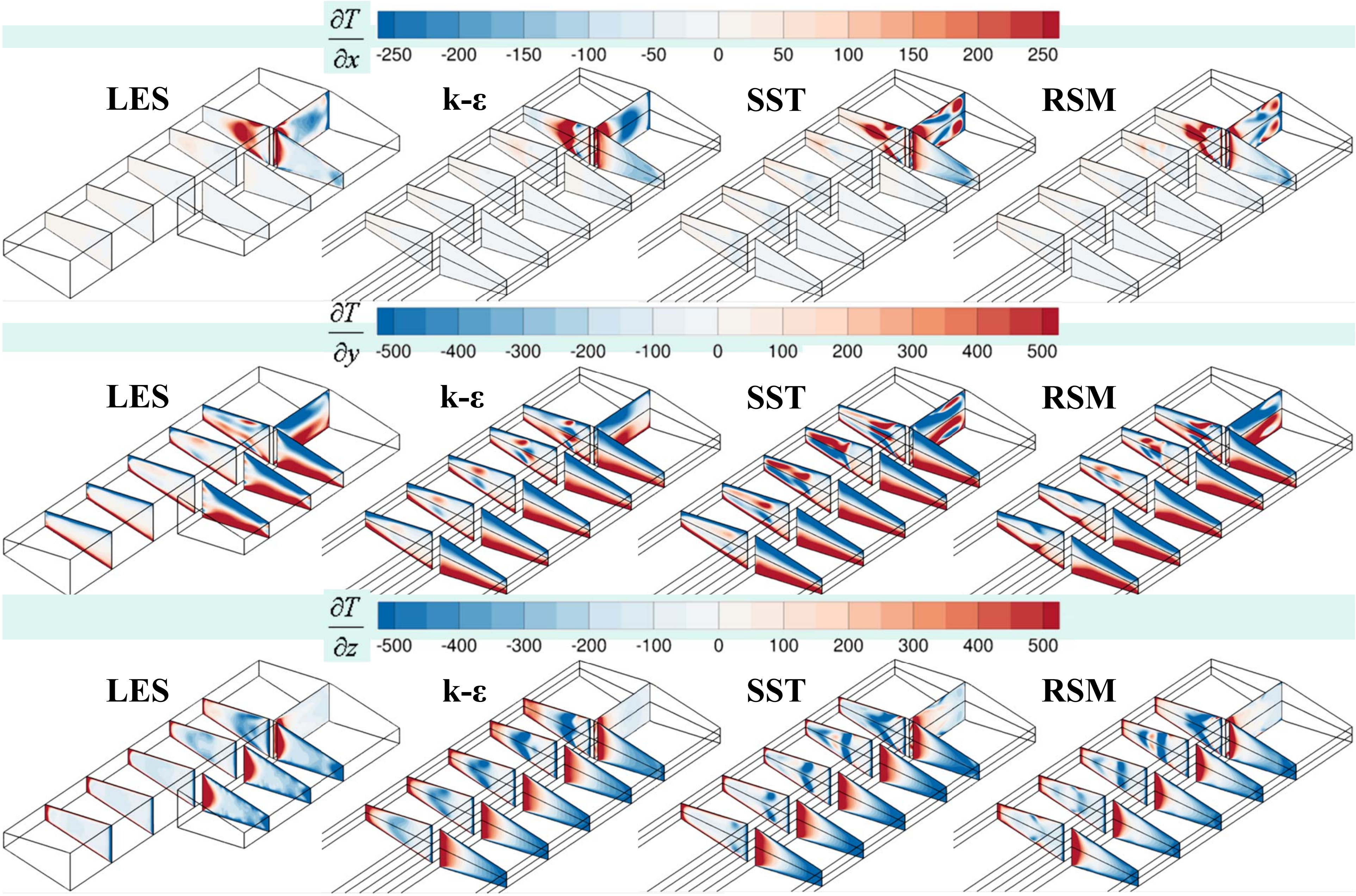
Eddy Diffusivity Hypothesis #*RANS vs. LES)



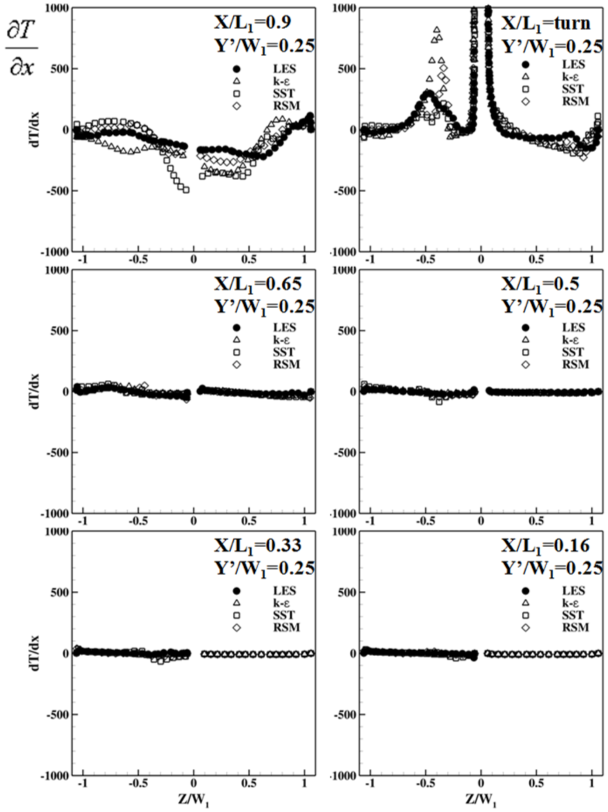


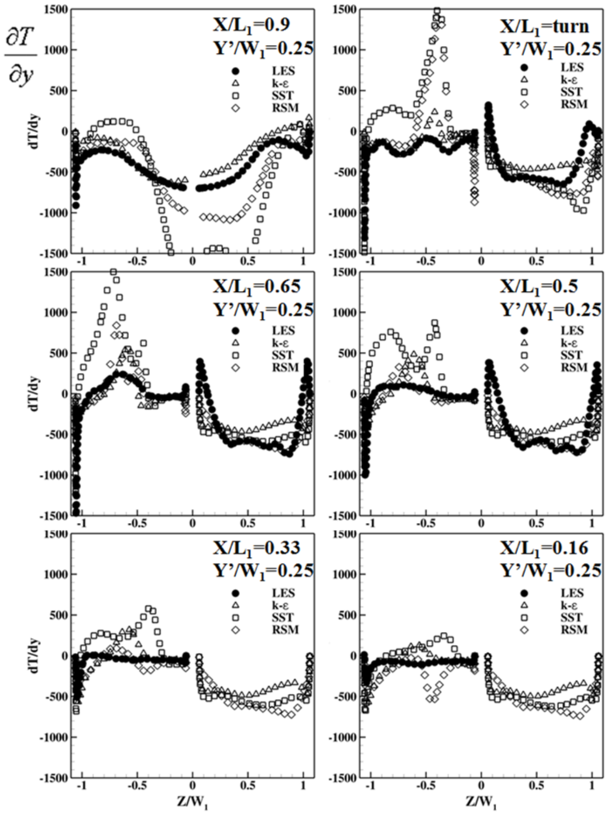


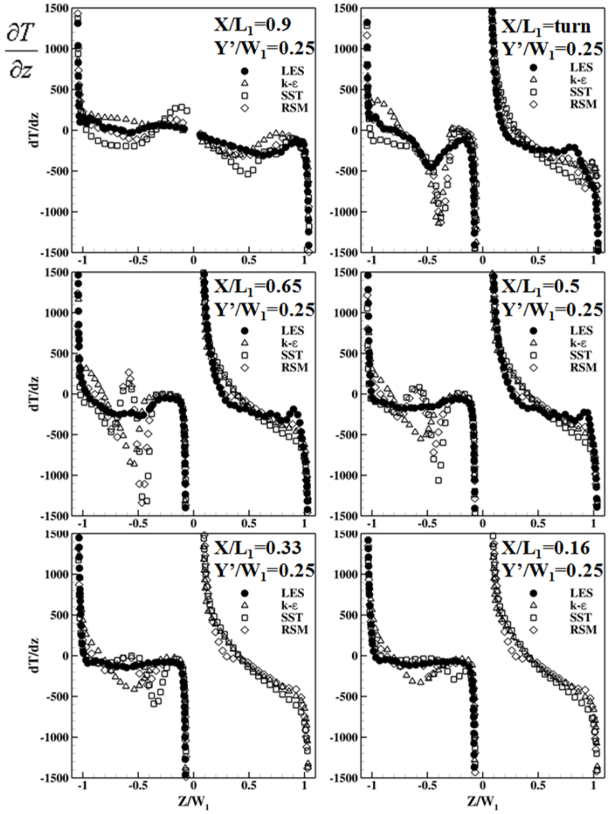
Mapping trapezoidal duct to square duct with the length of a side= W_1

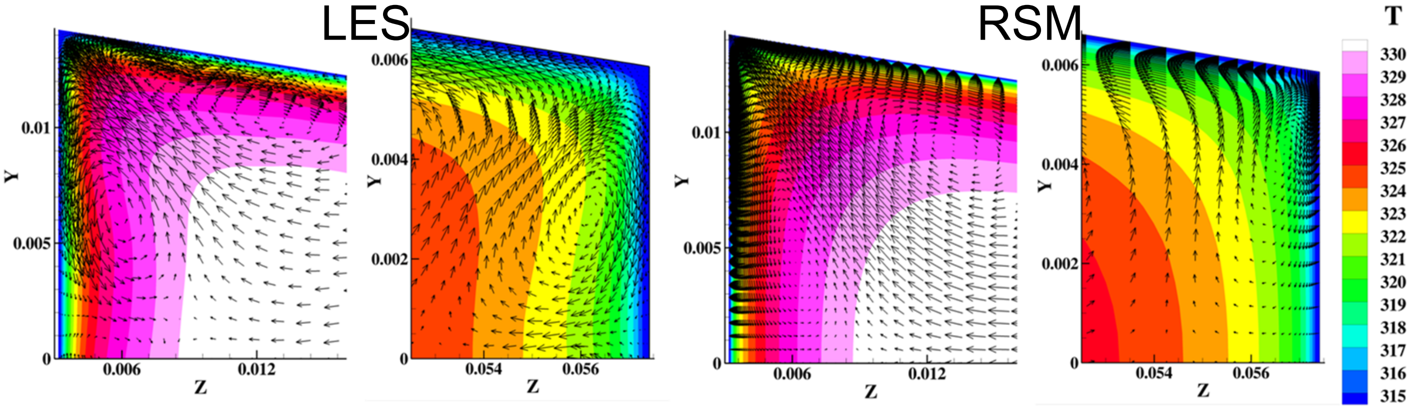


DoE – NETL & Ames Laboratory

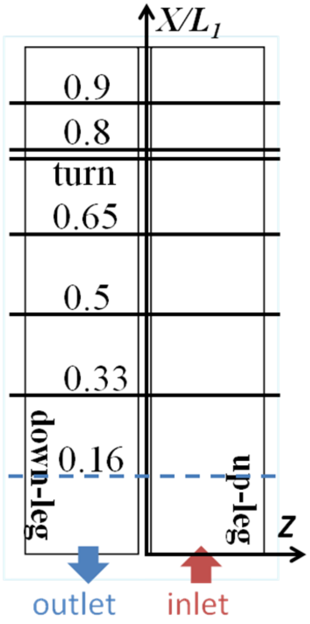

∂T/∂x
dT/dx
X/L$_1$=0.9
X/L$_1$=turn
X/L$_1$=0.65
X/L$_1$=0.5
X/L$_1$=0.33
X/L$_1$=0.16
Y'/W$_1$=0.25
LES
k-ε
SST
RSM
Z/W$_1$
1000
500
0
-500
-1000
-1
-0.5
0
0.5
1


∂T/∂y
dT/dy
X/L$_1$=0.9
X/L$_1$=turn
X/L$_1$=0.65
X/L$_1$=0.5
X/L$_1$=0.33
X/L$_1$=0.16
Y'/W$_1$=0.25
LES
k-ε
SST
RSM
Z/W$_1$
1500
1000
500
0
-500
-1000
-1500
-1
-0.5
0
0.5
1

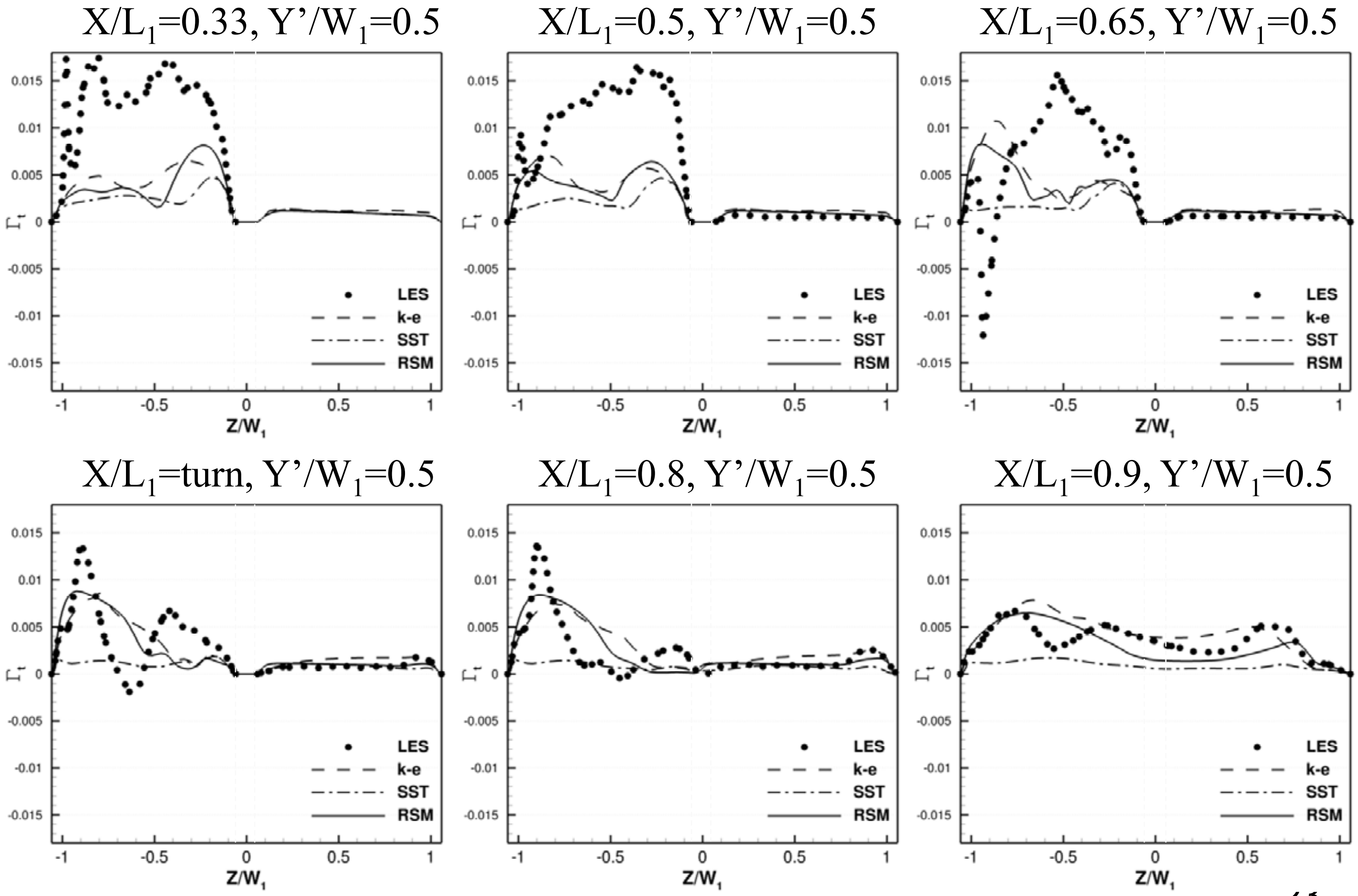

∂T/∂z
dT/dz
X/L$_1$=0.9
X/L$_1$=turn
X/L$_1$=0.65
X/L$_1$=0.5
X/L$_1$=0.33
X/L$_1$=0.16
Y'/W$_1$=0.25
LES
k-ε
SST
RSM
Z/W$_1$
1500
1000
500
0
-500
-1000
-1500
-1
-0.5
0
0.5
1

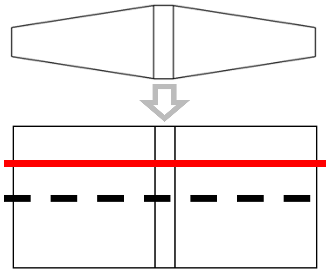

LES
RSM
Y
Z
0.01
0.005
0
0.006
0.012
0.006
0.004
0.002
0.054
0.056
T
330
329
328
327
326
325
324
323
322
321
320
319
318
317
316
315

Eddy Diffusivity (RANS vs. LES)



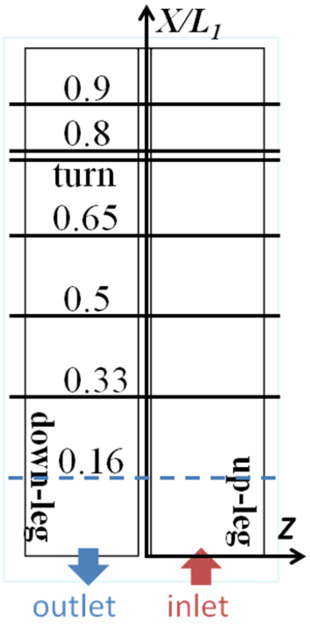
$$\Gamma_{t,RANS} = \frac{\mu_t}{\mathrm{Pr}_t} \quad \Leftrightarrow \quad \Gamma_{t,LES} = \frac{-\overline{u_i'T'}\,\dfrac{d\overline{T}}{dx_i}}{\dfrac{d\overline{T}}{dx_j}\,\dfrac{d\overline{T}}{dx_j}}$$



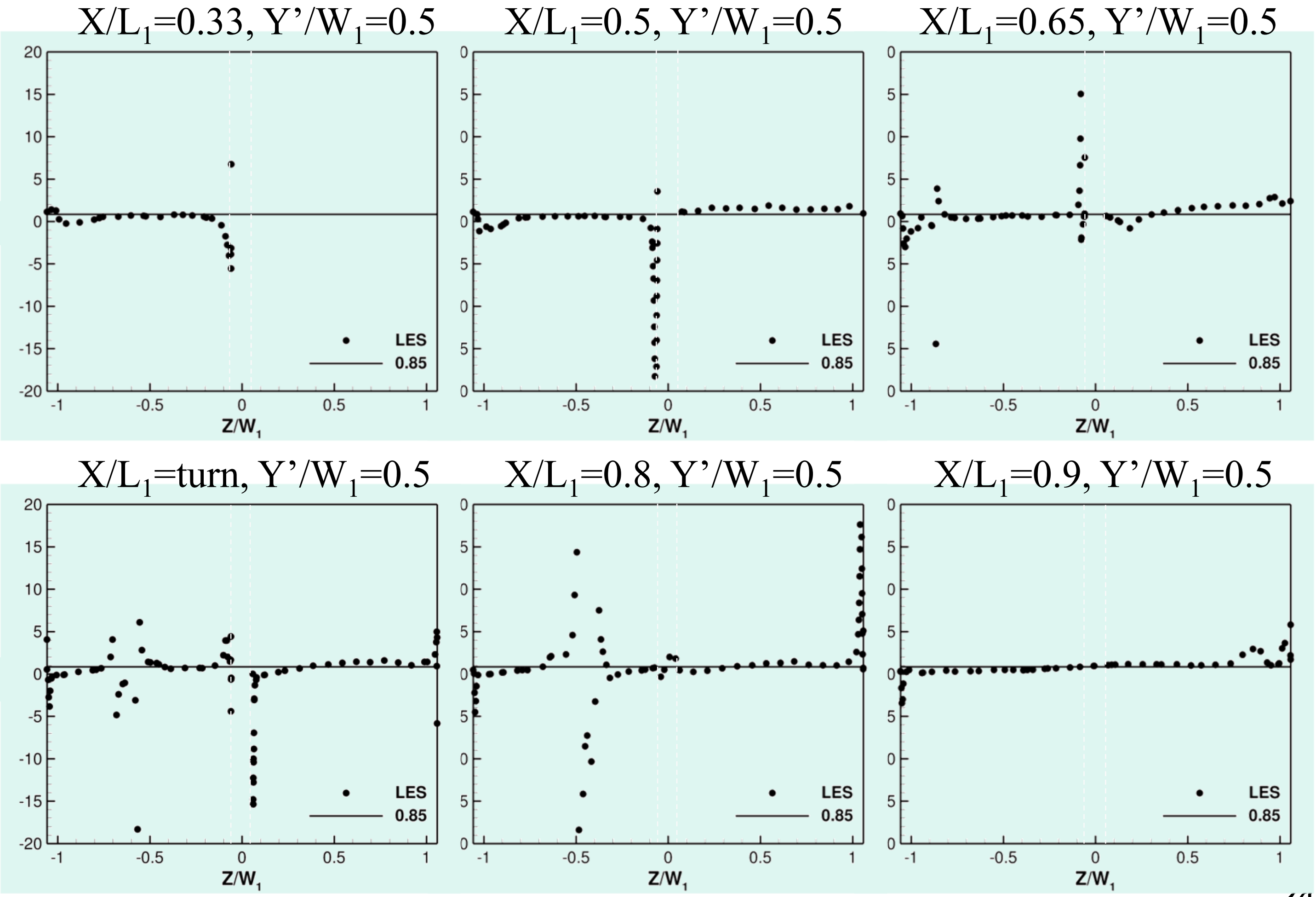


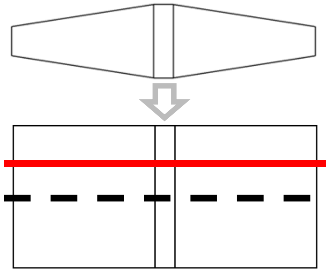
Mapping trapezoidal duct to square duct with the length of a side= W_1

Eddy Diffusivity Hypothesis: Prandtl Number(RANS vs. LES)

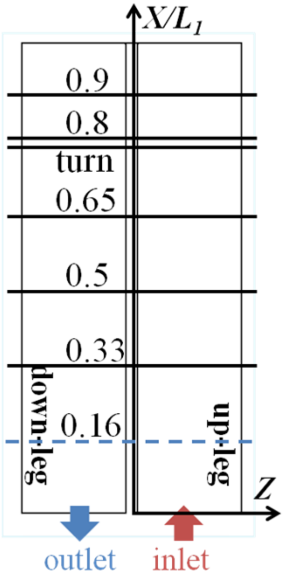


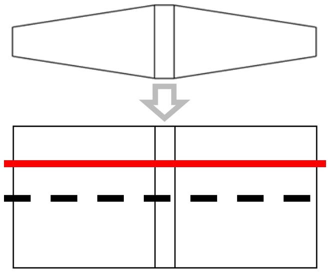
$$\mathrm{Pr}_{t,RANS} = 0.85 \Leftrightarrow \mathrm{Pr}_{t,LES} = \frac{\mu_t}{\Gamma_{t,LES}}$$



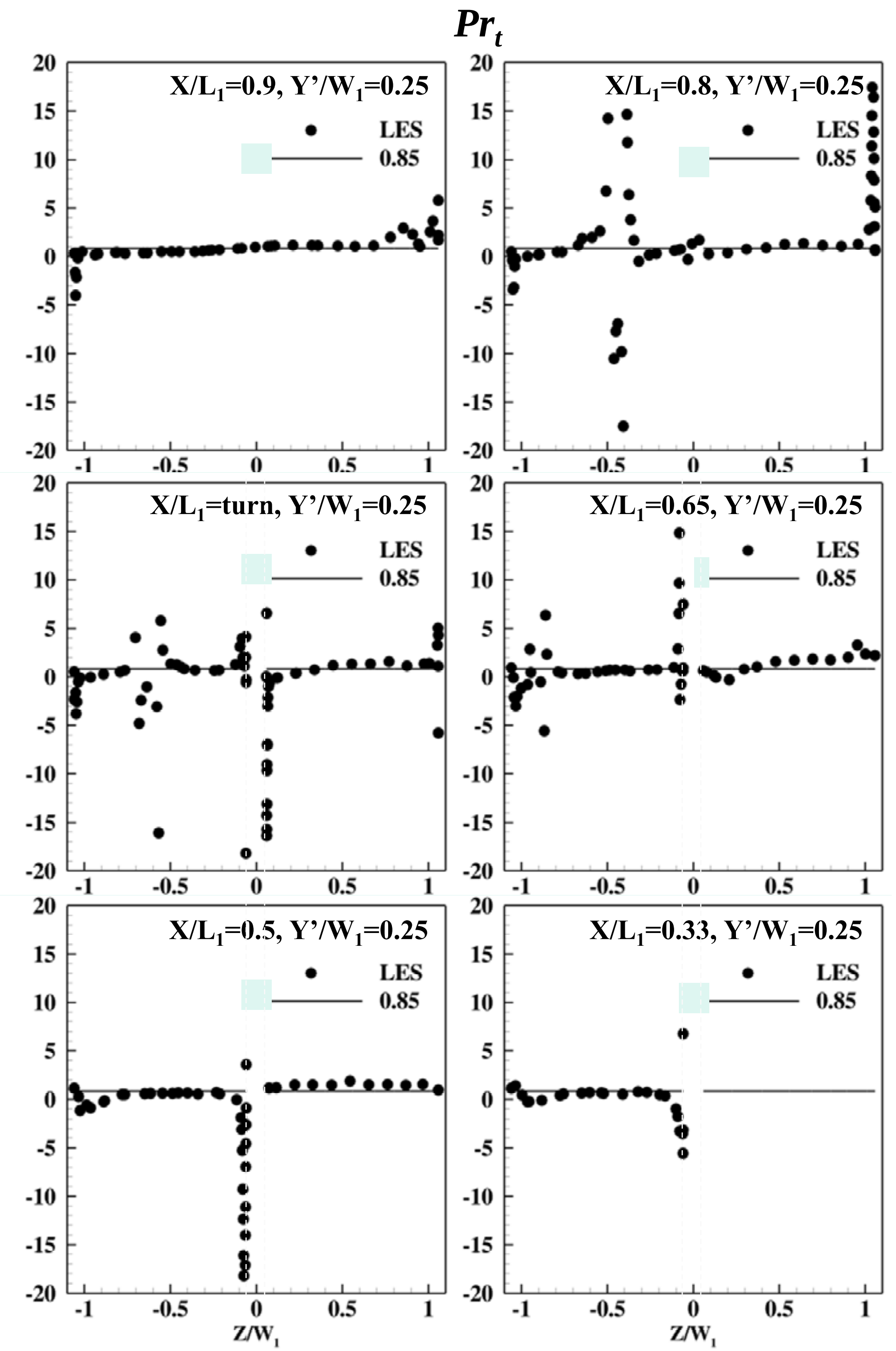


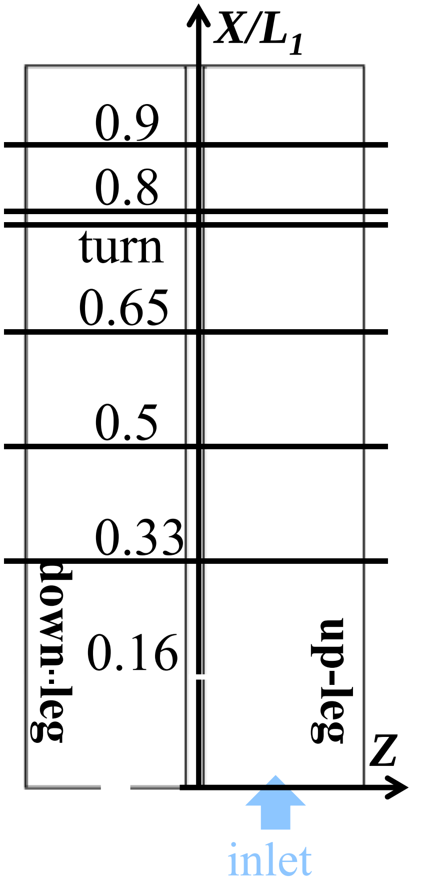
Mapping trapezoidal duct to square duct with the length of a side= W_1





Mapping trapezoidal duct to square duct with the length of a side= W_1





Summary

RANS:

- Can predict average HTC OK.
- Cannot predict HTC distributions in down-leg because steady and unsteady RANS cannot predict the shedding of vortices at the U-bend separator.

LES:

- Grid resolution based on DNS & satisfying -5/3 power law.
- LES inflow boundary condition rigorously addressed (did not use vortex method).
- LES can resolve all of the flow physics as expected if done right, but it did show why RANS failed.
- LES provided data to improve modeling of pressure strain, turbulent diffusion, and modeling of $\overline{u_i'T'} = -\Gamma_t \frac{\partial T}{\partial x_i}$

Effects of Density and Blowing Ratios on Turbulent Structure and Effectiveness of Film Cooling

Zach Stratton and Tom I-P. Shih
School of Aeronautics and Astronautics
Purdue University

DoE – NETL & Ames Laboratory

Introduction

Gas turbine engines can achieve greater efficiency by operating at higher turbine inlet temperatures.

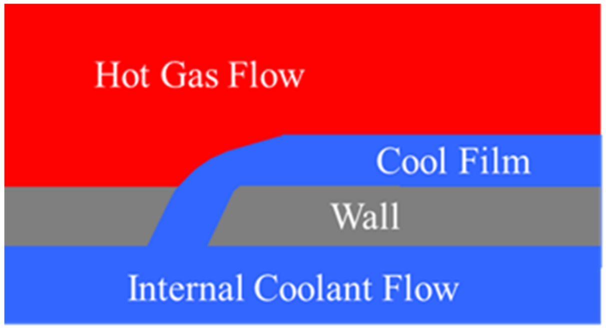
Today, inlet temperatures sought are upwards of

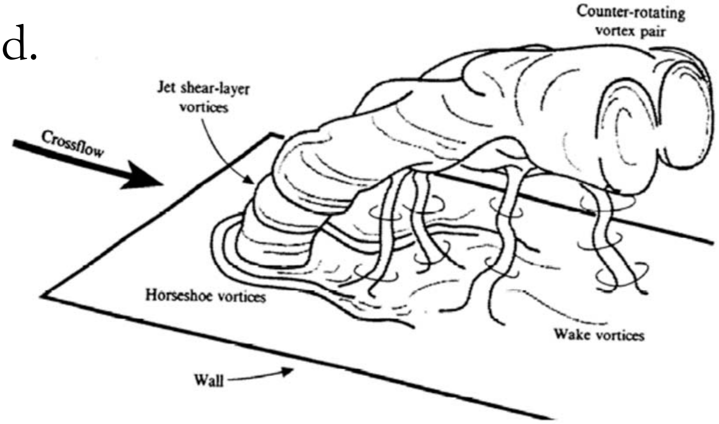
~1980° C (3600° F) for aircraft

Since these temperature are much greater than the allowable material temperatures, cooling is needed. Film cooling is an effective technique to cool. They involve

- unsteady wall jets
- boundary-layer-jet interaction
- highly sensitive to geometry and operating conditions

Cooling requires work so must be done with minimum cooling flow, which requires understanding. This understanding can be obtained by CFD.





Key Results from Previous CFD Studies of Film Cooling

Large scale flow structures near the hole are highly anisotropic such that fundamental assumptions of 2-equation models (Boussinesq) breakdown (Mahesh, 2012; Sarkar, 2014; Sakai, 2014).

Lateral spreading of the jet (coolant) is generally under predicted in RANS due to strength and size of the counter-rotating vortex pair being overpredicted (Hassan, 2006; Harrison, 2008; Stratton, 2015).

2-eq models with DNS based anisotropic corrections significantly improve predictions. (Azzi, 2002; Li, 2011; Xueying, 2014).

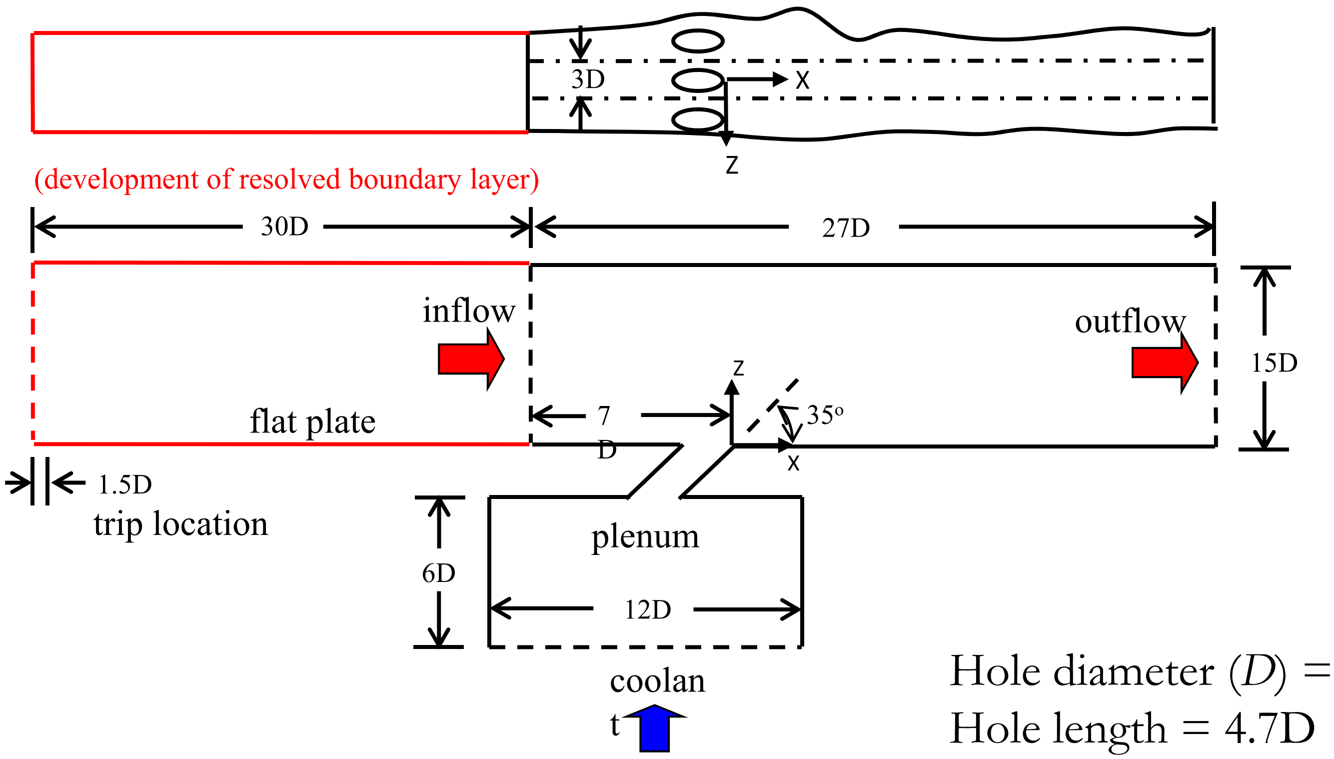
Though LES has the ability to predict correctly, it expensive even with existing computing capabilities. One way to reduce cost is not resolving the turbulence in the boundary layer approaching the cooling jet (Acharya, 2010; Bodart, 2013; Ziefle, 2013)

How BR, DR, and hole shape affect turbulence and its effects on adiabatic effectiveness is still not entirely clear. This understanding is crucial for further design insight and model development for RANS.

Objective

- Use LES to investigate the effects of resolving and not resolving the turbulent boundary layer approaching the cooling jet.
- Determine how physics and turbulence scales with blowing ratio and density ratio

Problem Description



Hot Gas (Air)

$T_\infty = 329^o$ K (DR = 1.6)

$T_\infty = 296^o$ K (DR = 1.1)

u = u(y); $Re_\theta = 670$

$u_\infty = 36.35$ m/s

Cool gas (Air)

$T_c = 203^o$K (DR = 1.6)

$T_c = 269^o$K (DR = 1.1)

Hole diameter (*D*) = 2.61 mm
Hole length = 4.7D
Hole spacing = 3D
Hole angle = 35º
Adiabatic walls

Problem Description

Resolved Turbulent Boundary Layer:

Trip laminar boundary layer at $\mathrm{Re}_\theta = 270$ with body-force trip

$$f = \frac{2D_c}{\pi\, x_{\mathrm{ref}}\, y_{\mathrm{ref}}\, z_{\mathrm{ref}}} \sin^2\left(\pi \frac{z-Z}{z_{\mathrm{ref}}}\right) \times \exp\left[-\left(\frac{x-X}{x_{\mathrm{ref}}}\right)^2 \left(\frac{y-Y}{y_{\mathrm{ref}}}\right)^2\right]$$

Mean Boundary Layer:

1/7th turbulent boundary layer profile

Boundary Layer	DR	BR	VR
Mean Profile	1.1	0.5	0.455
Mean Profile	1.1	1.0	0.909
Mean Profile	1.6	0.5	0.313
Mean Profile	1.6	0.5	0.625
Resolved	1.1	0.5	0.455
Resolved	1.1	1.0	0.909
Resolved	1.6	0.5	0.313
Resolved	1.6	0.5	0.625

Formulation, Numerical Method, & Code

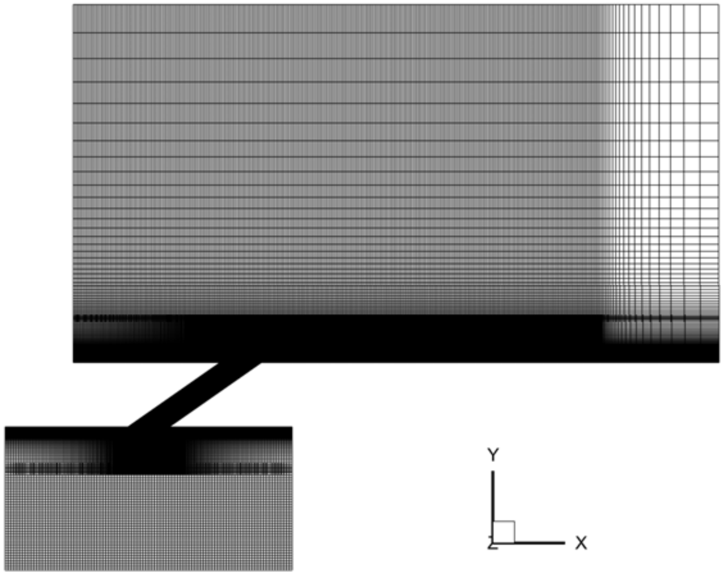
Governing Equations: "Compressible" Unfiltered Navier-Stokes

Perfect gas
$\mu = \mu(T)$ (Sutherland's Law)
$\gamma = 1.4$
Pr = 0.72 (air)
$\lambda = -2/3\mu$ (Stokes' hypothesis)

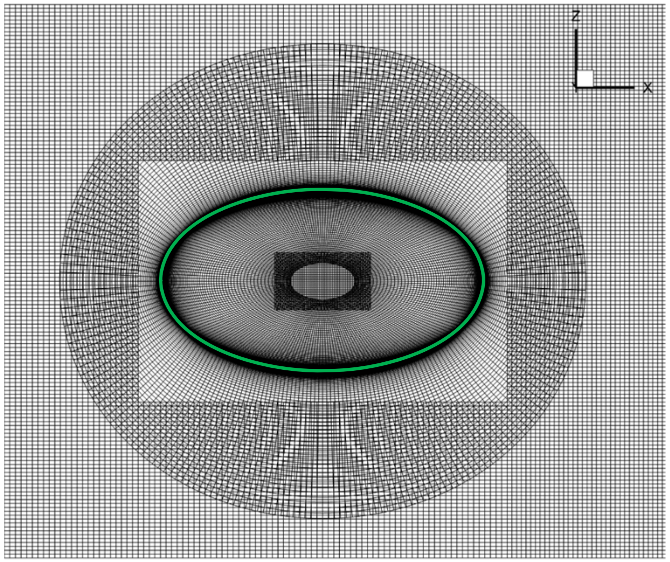
Code: FDL3DI (Implicit LES)

Finite difference on boundary-fitted grid with overset capability
2nd order implicit in time
6th order compact spatial discretization
8th order filter – damp out high-frequency components of the solution

Grid System



22M grid points if not resolving BL
35M grid points if resolving BL



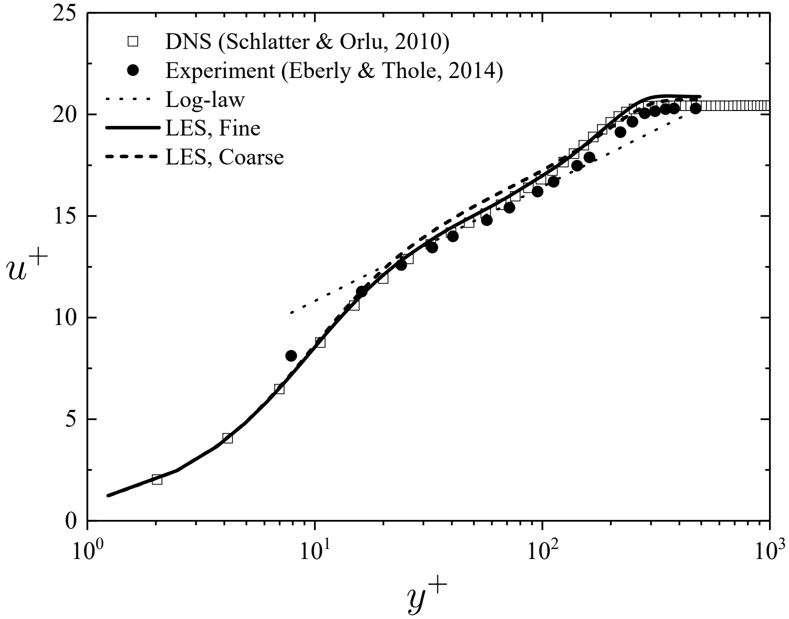
16 overset blocks
Inflate and extrapolate at the outlets
4 cells within $y^+ = 1$
50 cells within $y^+ = 100$

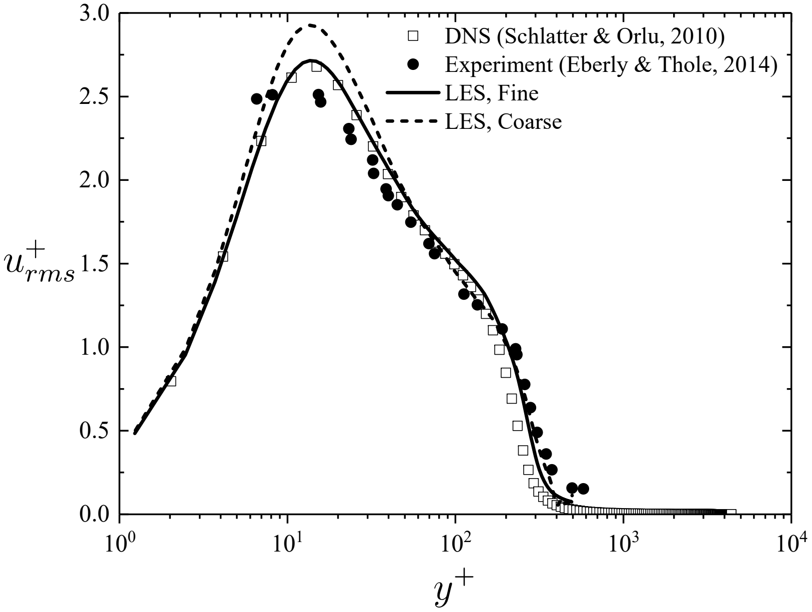
Verification: Boundary Layer

Want to ensure turbulent BL is resolved by LES.

Excellent agreement is achieved on the fine mesh, and this resolution is used for our study

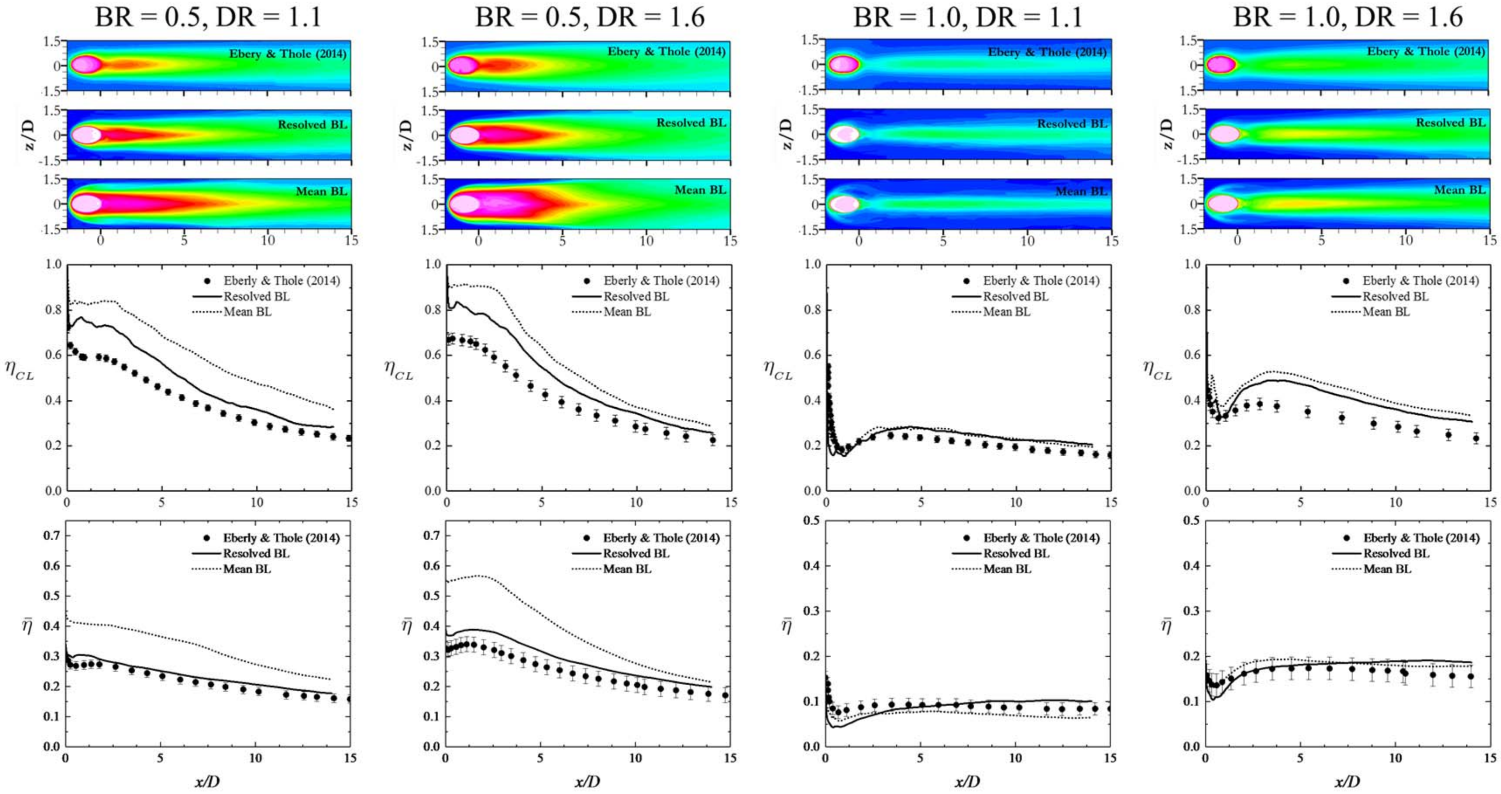
Mesh	Δx^+	Δy_w^+	Δy_e^+	Δz^+
Coarse	17	0.4	10	8
Fine	9	0.4	8	5





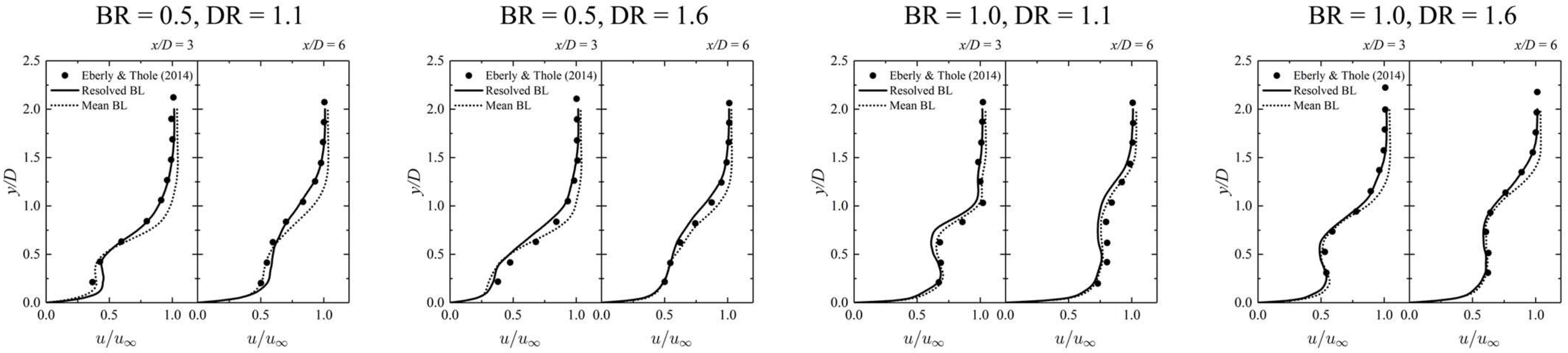
DoE – NETL & Ames Laboratory

Validation



Good agreement for resolved turbulent boundary layer cases
Mean Boundary layer overpredicts cooling at low BR

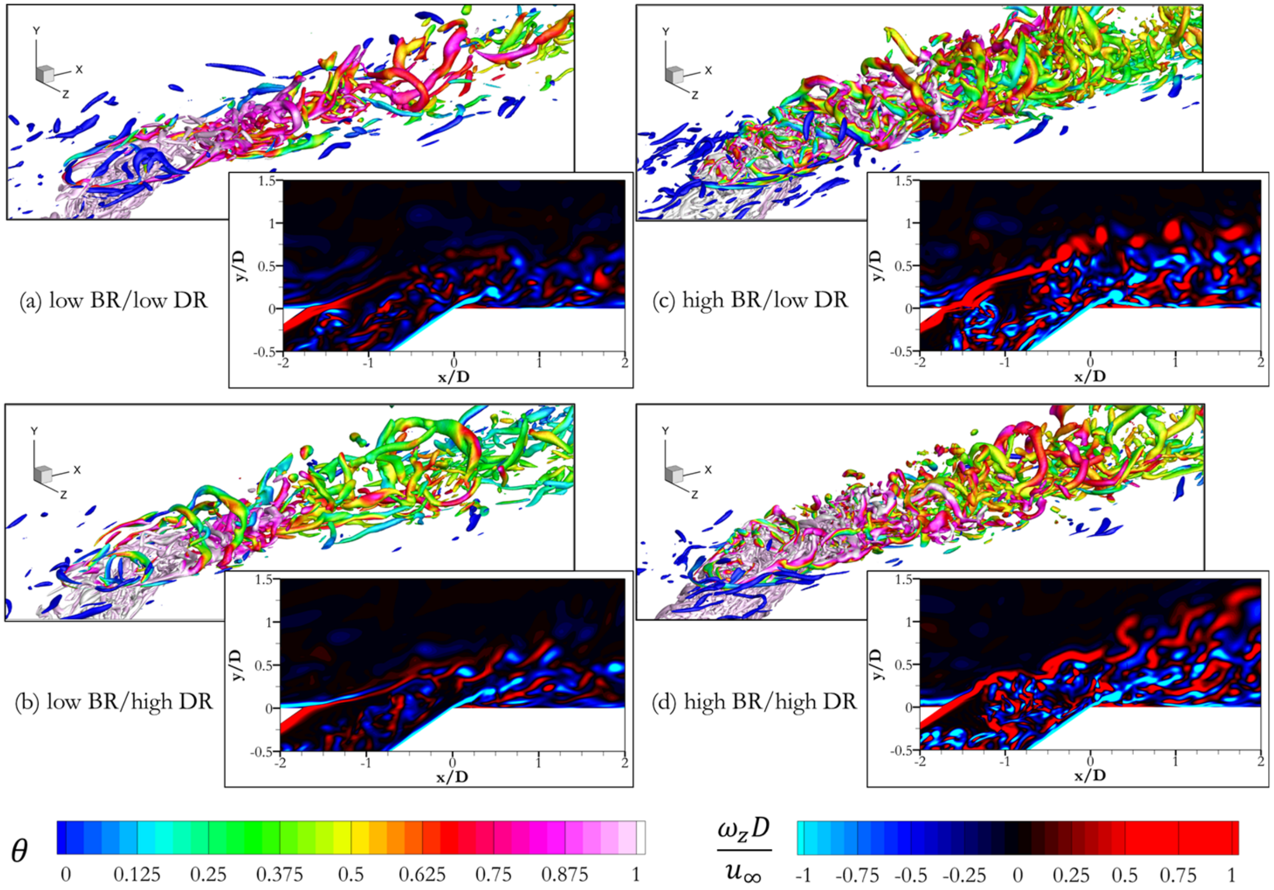
Validation



Good agreement for resolved turbulent boundary layer cases

Mean boundary layer overpredicts velocity at edge of jet

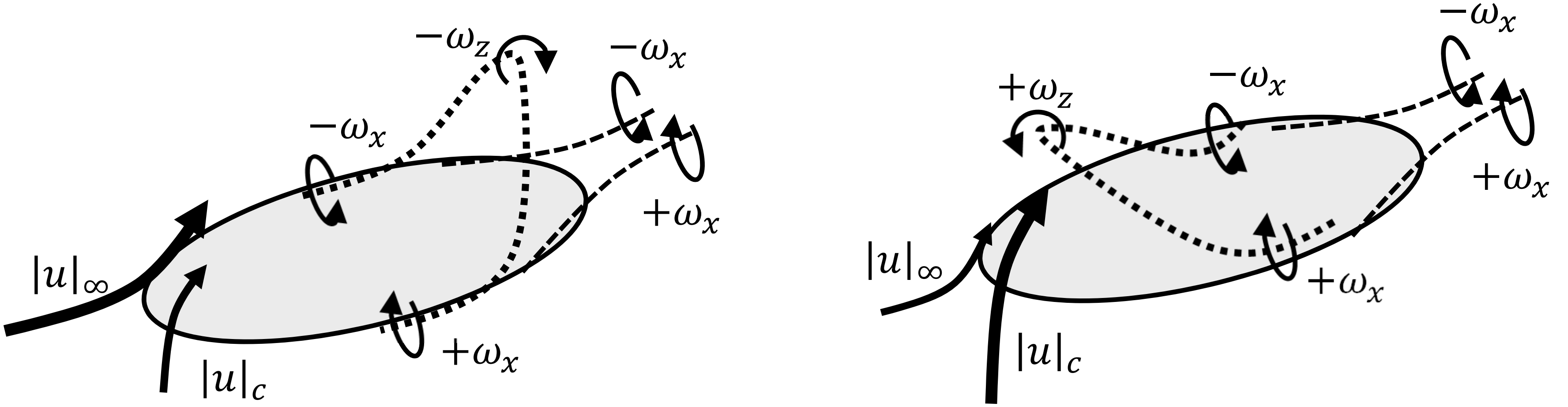
Instantaneous Results



Low VR:
Clockwise vortices (blue)

High VR:
Shear layer more unstable
Counter-clockwise
vortices (red)

Structure of Shear Layer Vortex

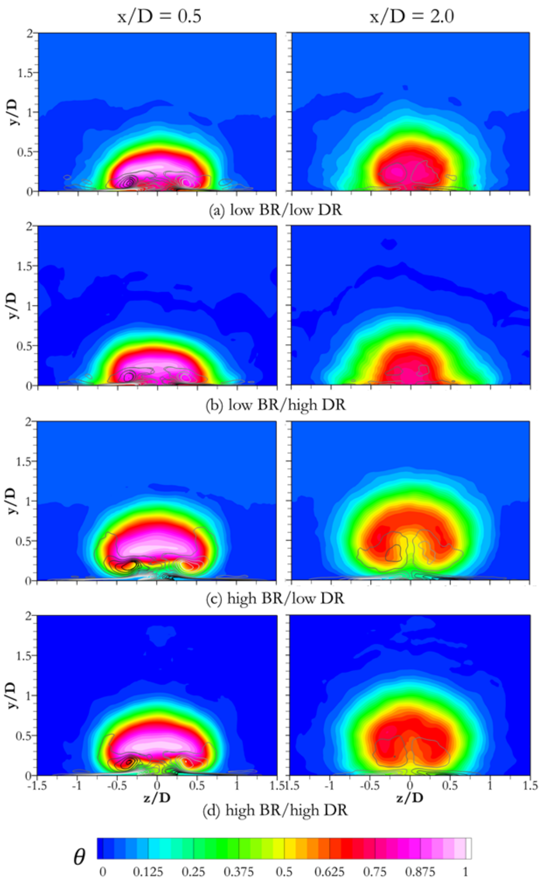


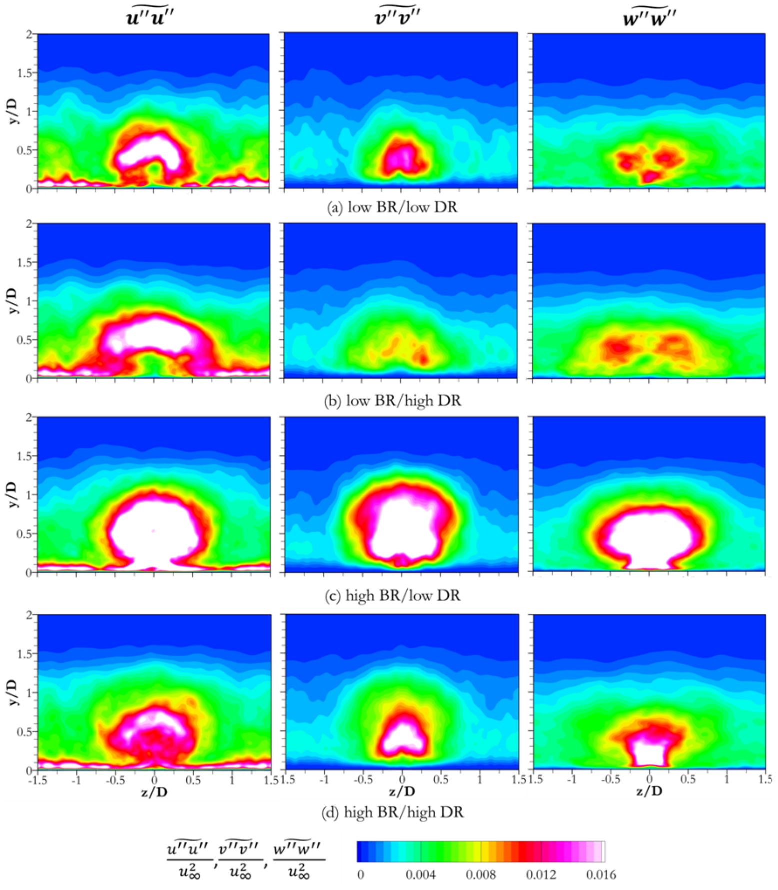
(a) low VR

(b) high VR

Shear layer vortices reverse direction at high VR

Temperature, Vorticity, and Normal Stresses (x/D = 2.0, TBL)





<u>Low VR:</u>
More spreading
Weaker CRVP

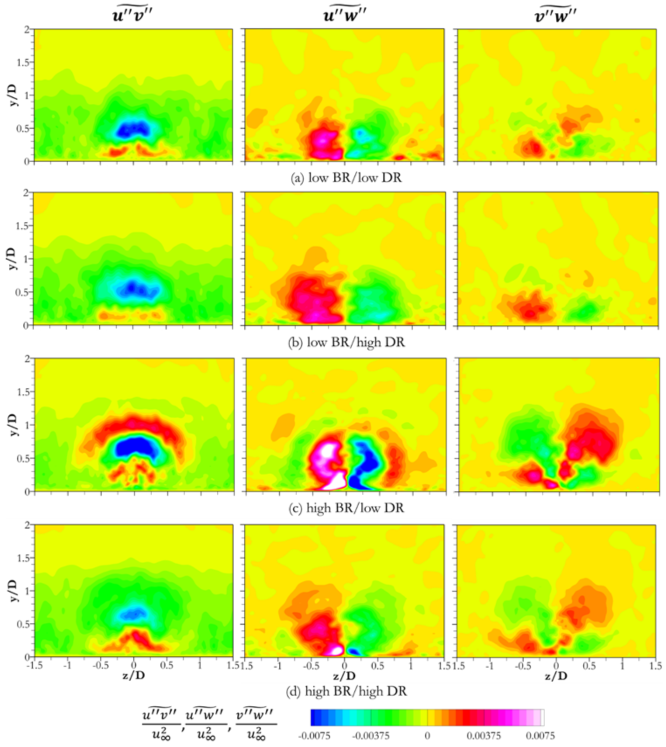
<u>High VR:</u>
Jet lifts off
Stronger CRVP entrains more hot-gas resulting in u-shape

Turbulence tends to constrict and increase as VR increases

DoE – NETL & Ames Laboratory

PURDUE
UNIVERSITY

Shear Stresses and Heat Fluxes (x/D = 2, TBL)

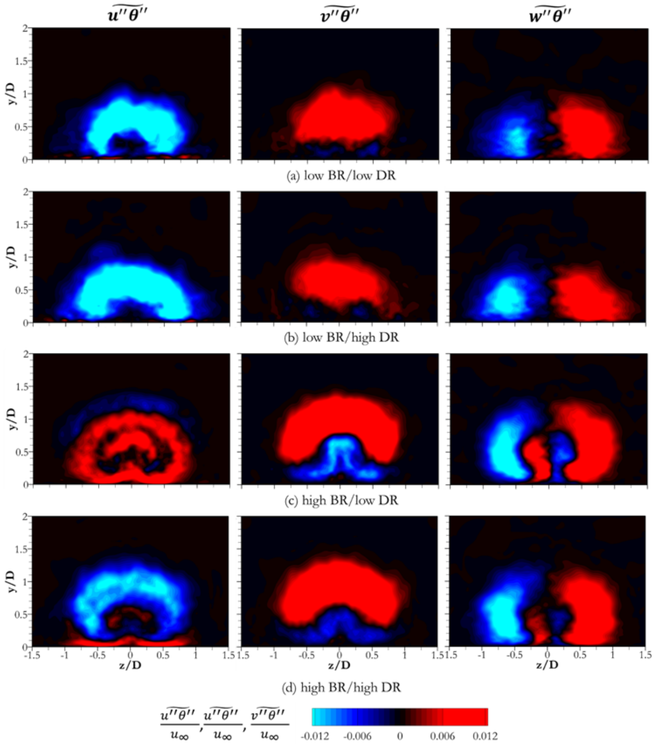


(a) low BR/low DR

(b) low BR/high DR

(c) high BR/low DR

(d) high BR/high DR



(a) low BR/low DR

(b) low BR/high DR

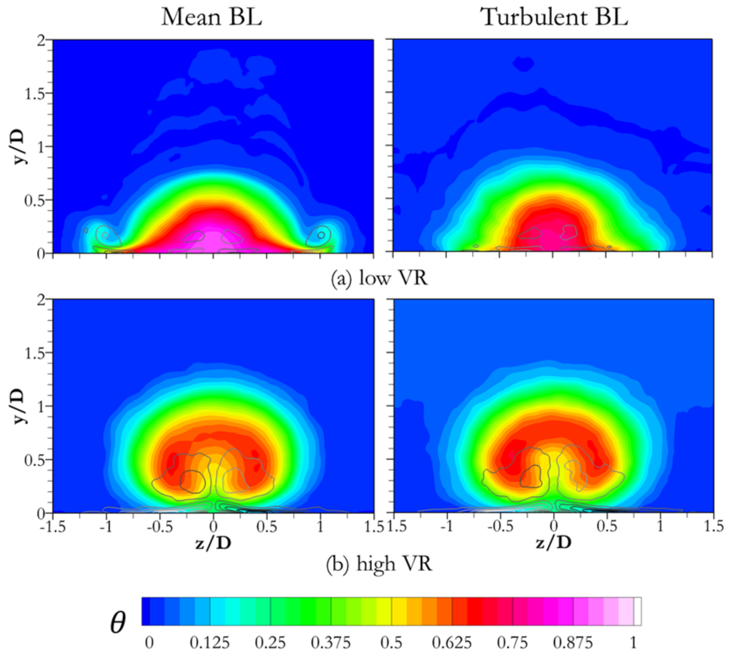
(c) high BR/low DR

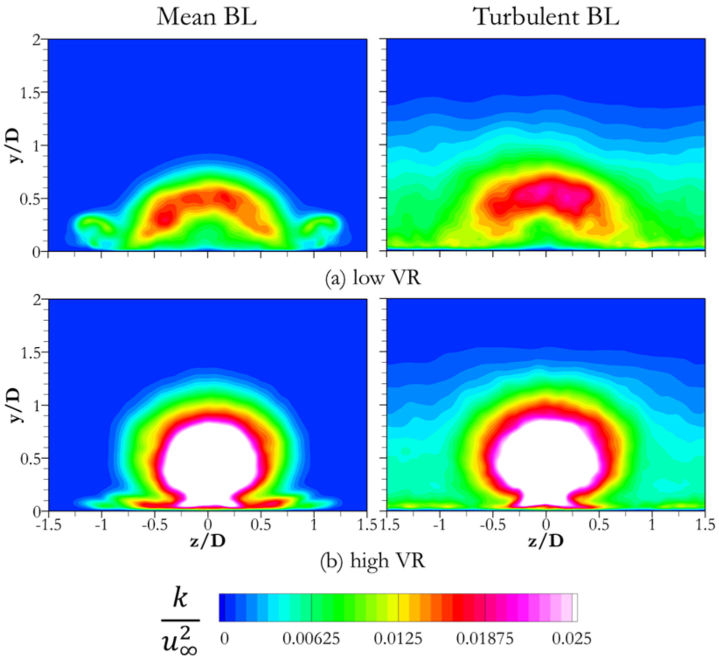
(d) high BR/high DR

Turbulence tends to follow CRVP and scale with VR

At high VR there is a change in the physics that completely changes the turbulent mixing and heat transfer

Mean vs. Resolved Turbulent Boundary Layer





Horseshoe vortex helps spread coolant at low VR, but little affect at high VR

At low VR the TKE in the jet and boundary layer are similar

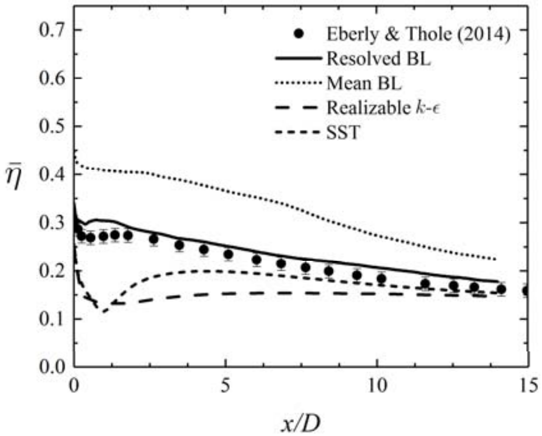
At high VR the jet is so energetic is does not tend to feel the effect of the boundary layer as much

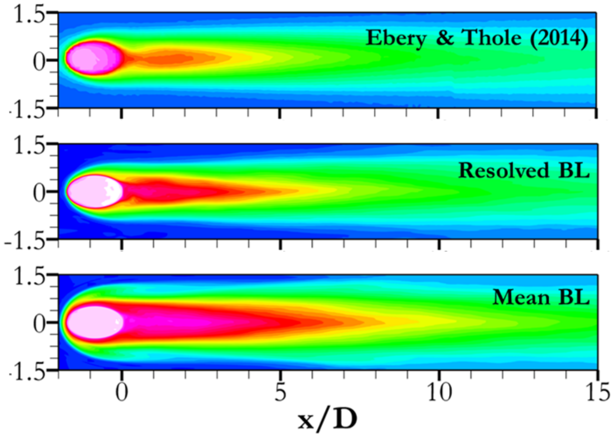
Conclusions

- ILES approach showed good agreement with experimental data
- At low V R (low BR/high DR) the shear layer vortex exhibited a negative z-vorticity, while high VR showed a positive z-vorticity.
- The impact of this change in vorticity manifested itself most noticeably in the $\widetilde{u''v''}$ and $\widetilde{u''\theta''}$ statistics, which highlight a shift in the nature of the large-scale mixing.
- The strength of the CRVP and turbulent mixing was found to scale with VR.
- A mean boundary layer profile is sufficient if the VR is high

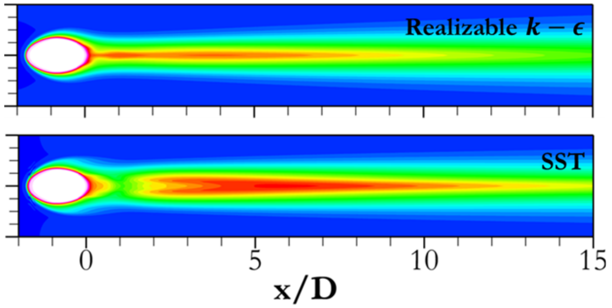
RANS vs LES

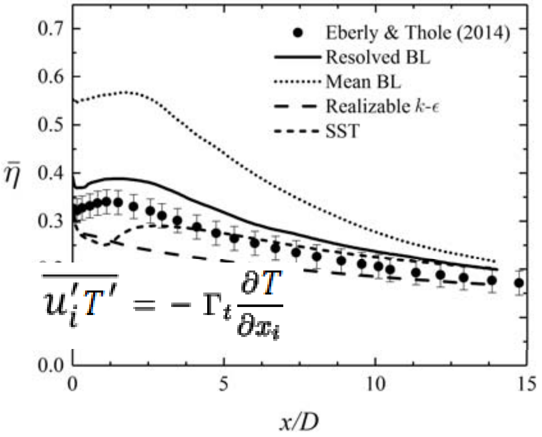
Validation



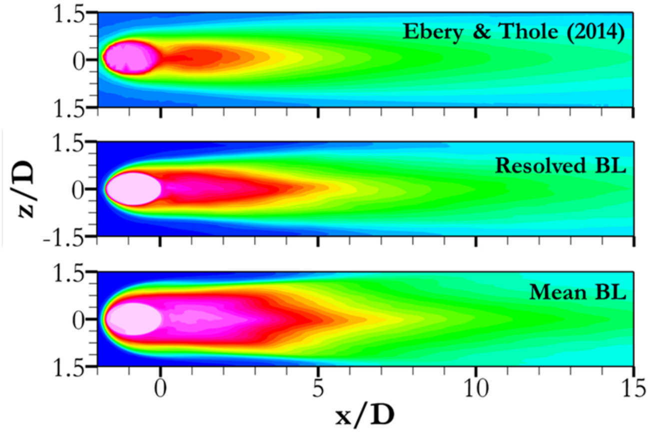


BR = 0.5, DR = 1.1

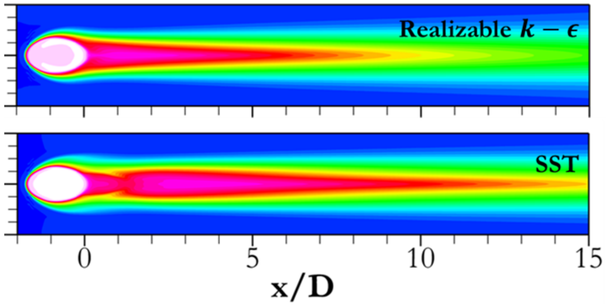




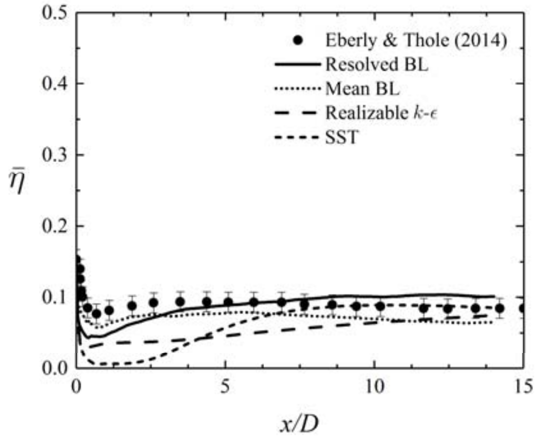
$$\overline{u_i'T'} = -\Gamma_t \frac{\partial T}{\partial x_i}$$

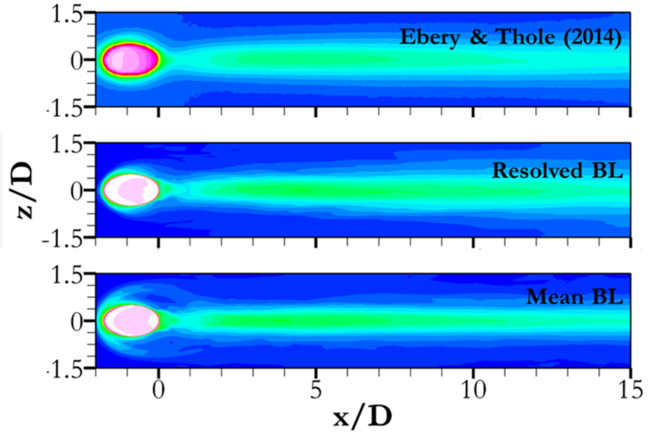


BR = 0.5, DR = 1.6

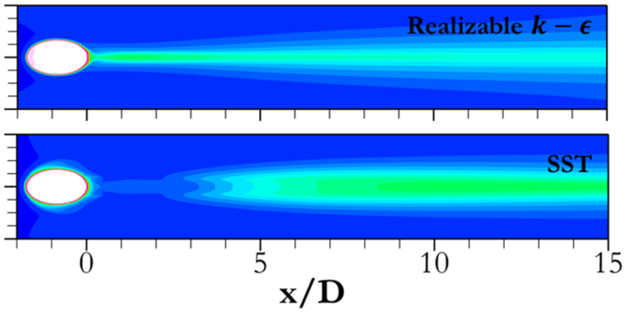


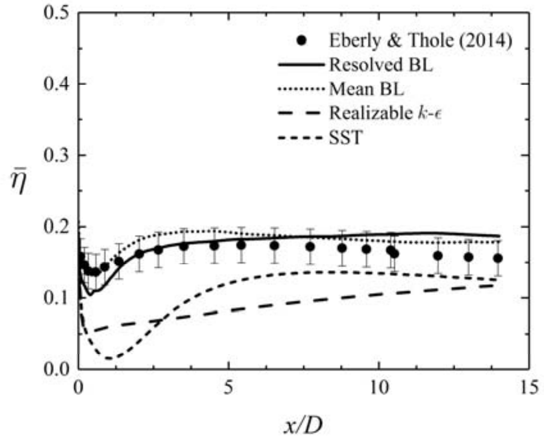
Validation

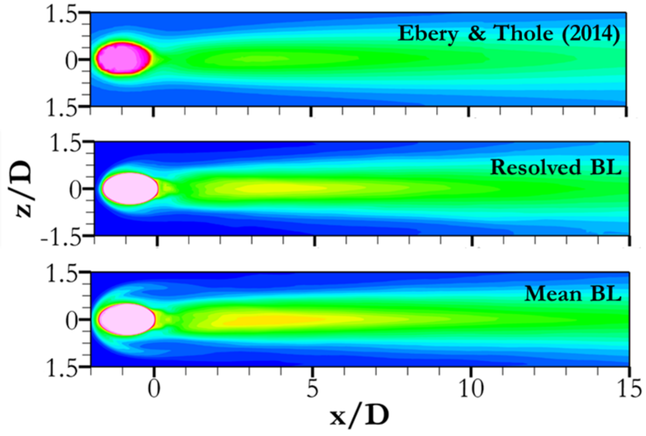




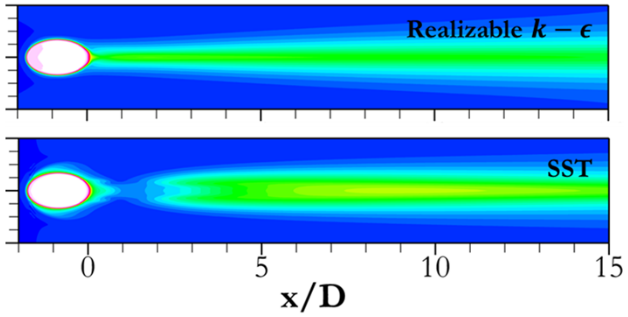
BR = 1.0, DR = 1.1



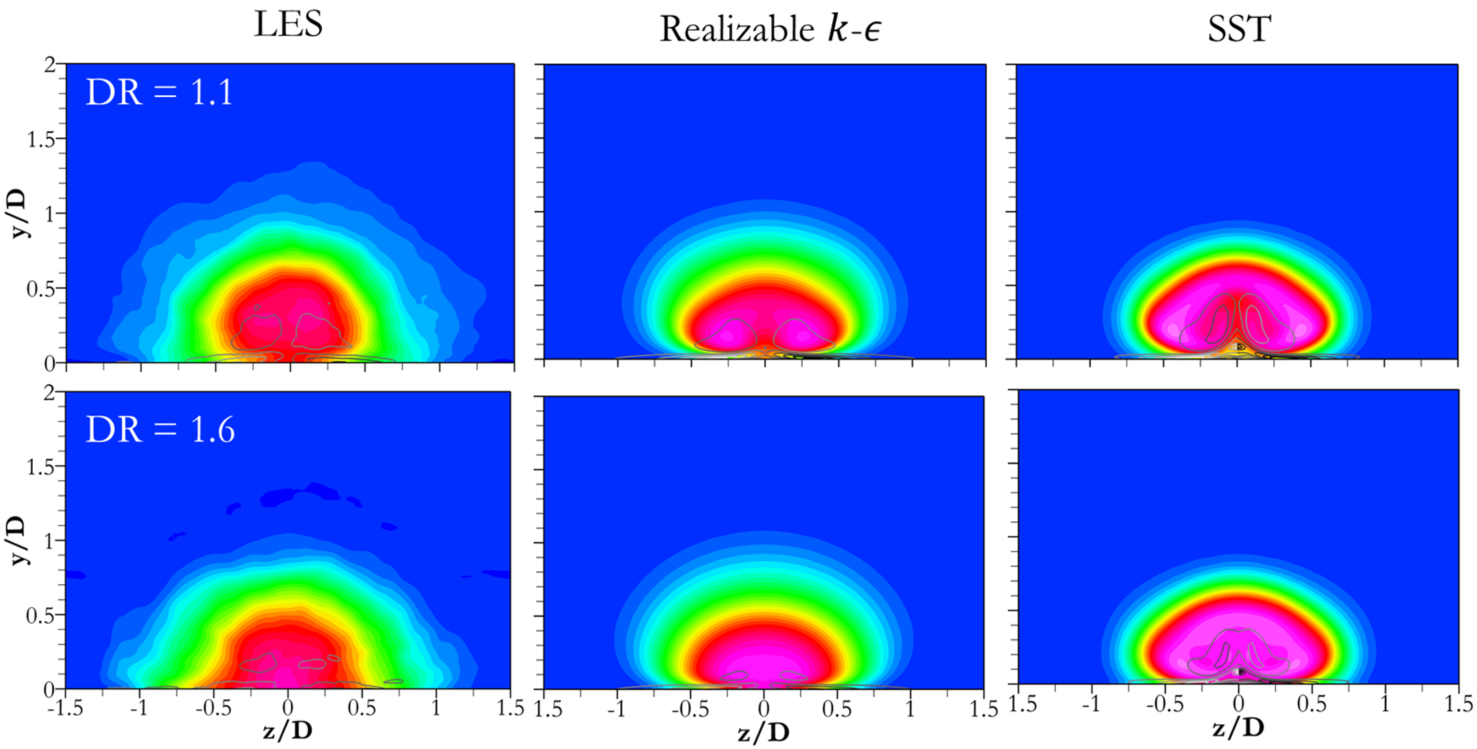




BR = 1.0, DR = 1.6



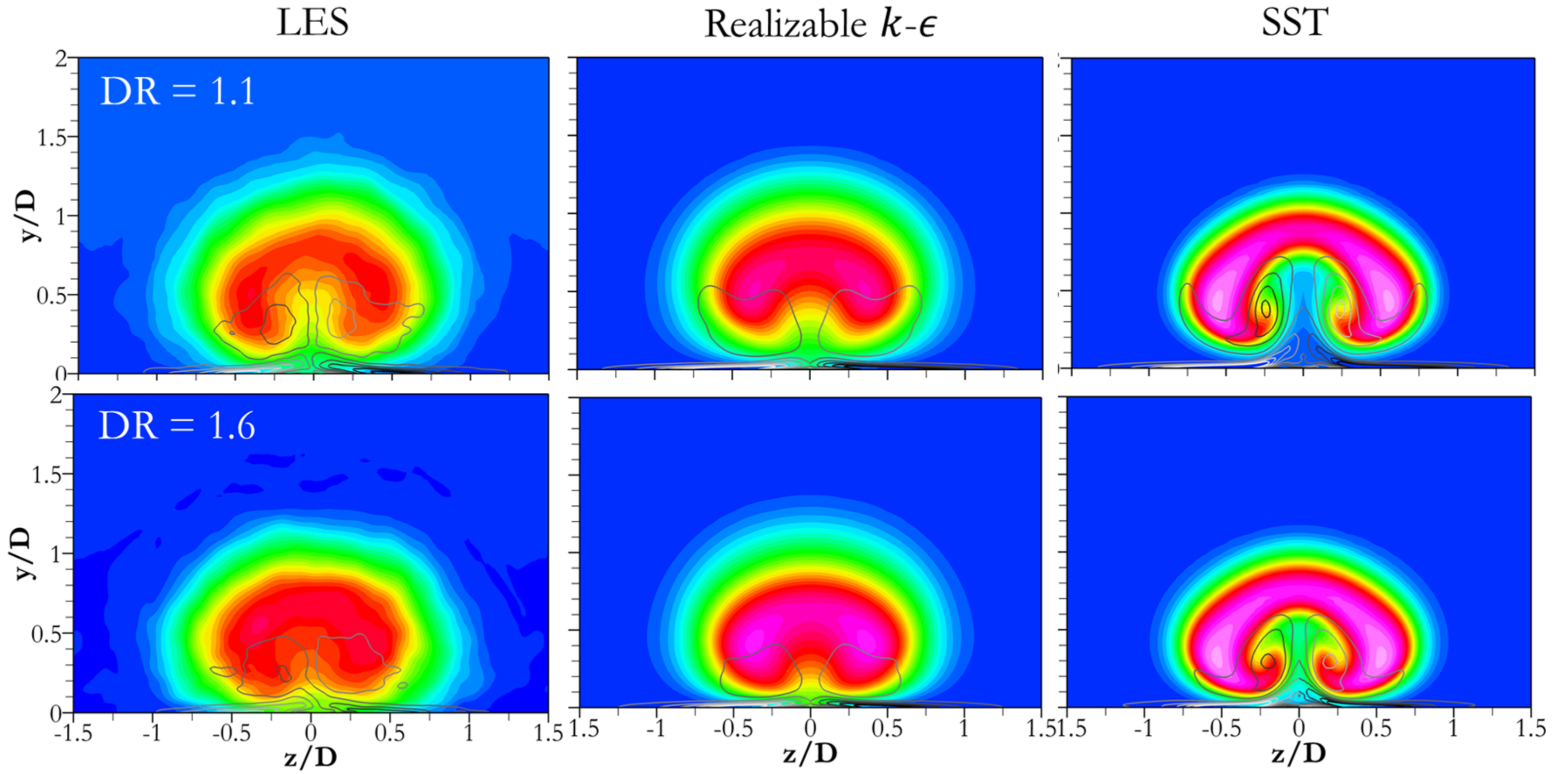
Temperature and Vorticity (x/D = 2.0, BR = 0.5)



RANS can not predict spreading correctly

RANS does predict increase of CRVP strength with VR, but incorrect magnitude

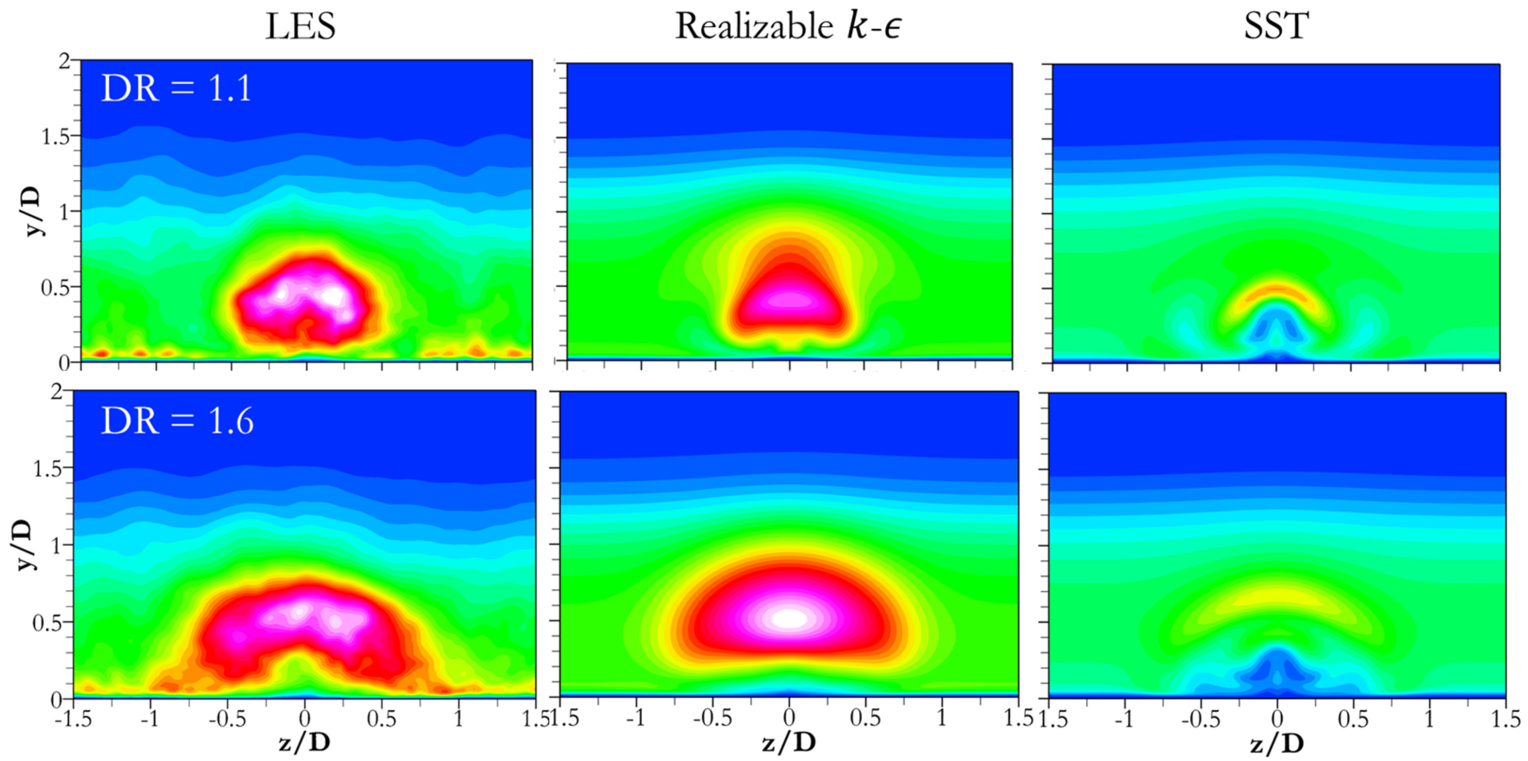
Temperature and Vorticity (x/D = 2.0, BR = 1.0)



RANS does not predict entrainment at high VR, but lift-off is seen

SST overpredicts strength of CRVP

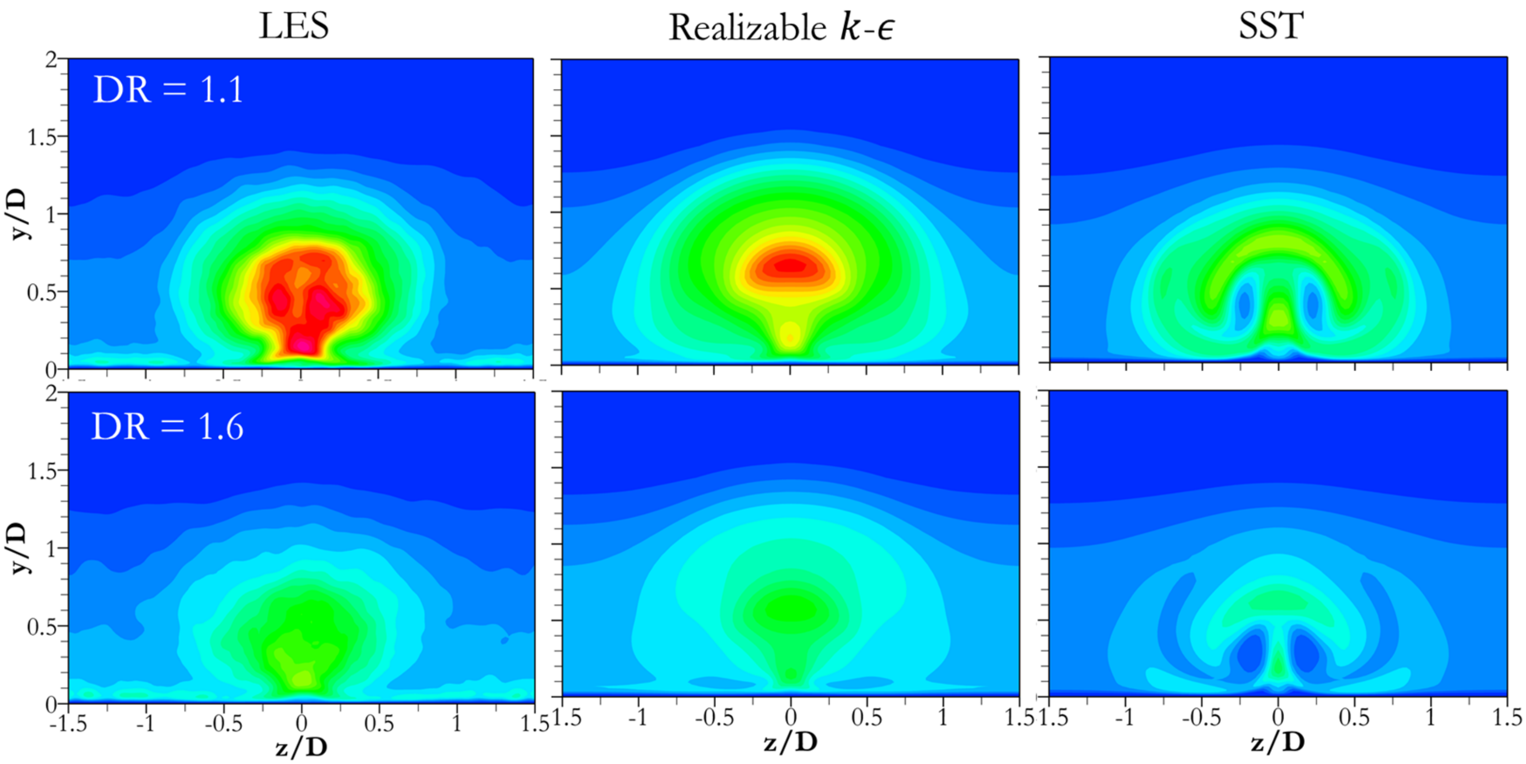
Turbulent Kinetic Energy (x/D = 2.0, BR = 0.5)



Realizable k-ϵ predicts magnitude of TKE, but cannot capture the curvature induced by CRVP

SST underpredicts the TKE

TKE (x/D = 2.0, BR = 1.0)

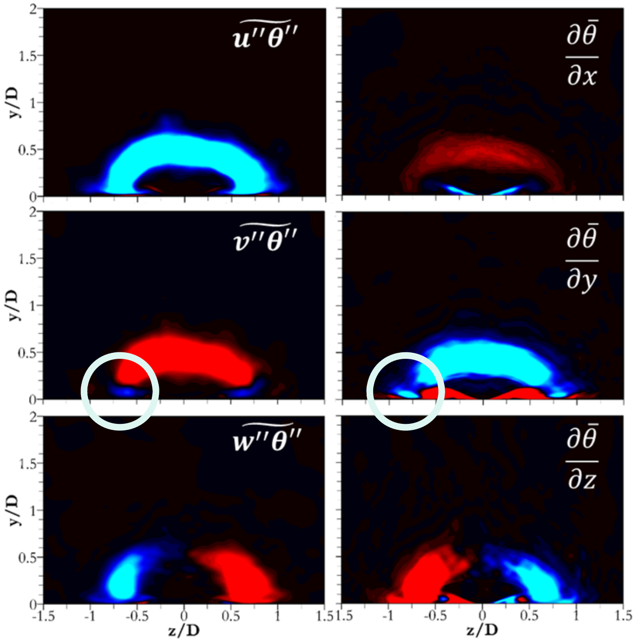


RANS generally can predict scaling of TKE with VR

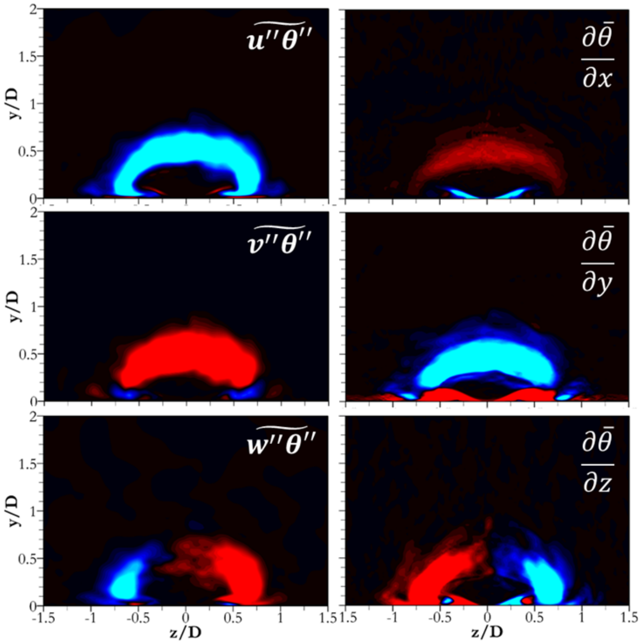
RANS underpredicts near wall TKE

Turbulent Heat Flux and Temperature Gradient, x/D = 0

BR = 0.5, DR = 1.6



BR = 0.5, DR = 1.1



RANS uses gradient diffusion model:

$$\widetilde{u_i''\theta''} = -\frac{\nu_t}{\underbrace{Pr_t}_{\alpha_t}}\frac{\partial\bar\theta}{\partial x_i}$$

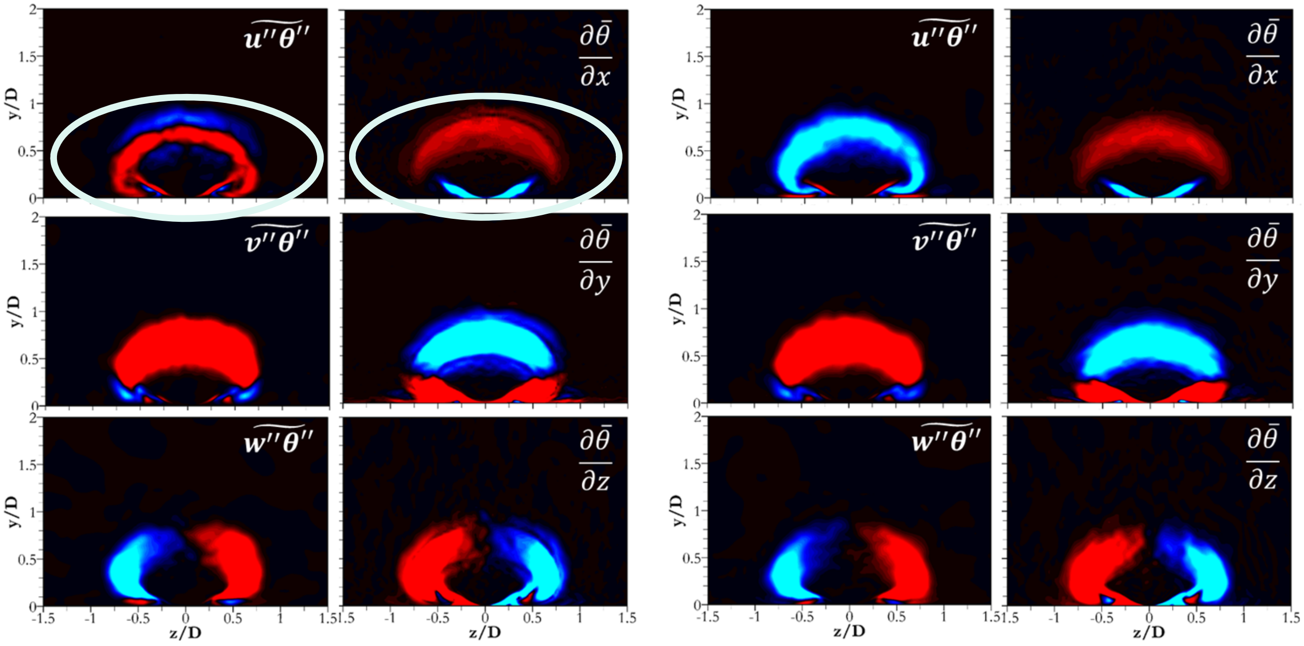
Turbulent heat flux and temperature gradient can be computed directly with LES to verify the model

At low VR, this model works well for the shear layer, but counter-gradient diffusion encountered at edge of jet

Turbulent Heat Flux and Temperature Gradient, x/D = 0

BR = 1.0, DR = 1.1

BR = 1.0, DR = 1.6



$$\widetilde{u_i''\theta''} = -\frac{\nu_t}{\underbrace{Pr_t}_{\alpha_t}}\frac{\partial\bar{\theta}}{\partial x_i}$$

At high VR, large scale mixing between shear layer vortices and strong CRVP results in counter-gradient diffusion is not captured by the simple gradient-diffusion model