2021 University Turbine Systems Research Project Review Meeting
8-10 November 2021

Analysis of Advanced Cooling Strategies for Gas Turbines

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Needs in the ELECTRIC POWER Sector

is driven by economics, regulations/policies, and national priorities such as those connected to climate change.

Our nation's goal to reach 100% carbon-free electricity by 2035 leads to many challenges and opportunities for gas turbines.

There are many pathways to transition from what we have today to one that is 100% carbon free!

For the gas-turbine hot section:

- Need to continue pushing all technologies – combustion, aerothermal, materials, control – to the limit for any fuel (NG, NG with H_2, H_2, ammonia, sCO_2) for increased efficiency, increased service life, and reduced cost.
- On GT aero/thermal, the need – for any fuel – continues to be
  - Improve cooling technology so cooling flow can be reduced and/or turbine inlet temperature increased
  - Further reduce aerodynamic losses

A lot of excellent work already done! To further advance the technologies and achieve 100% carbon-free electricity by 2035, need

- Even better understanding of the fundamentals in the flow & heat transfer to enable the innovations.
- Even better, faster, & cheaper design and analysis tools – both high-fidelity and reduced-order modeling & simulation.

Current Efforts

Tools:

- Develop/assess inflow BCs for LES and interface BCs for hybrid LES-RANS methods.

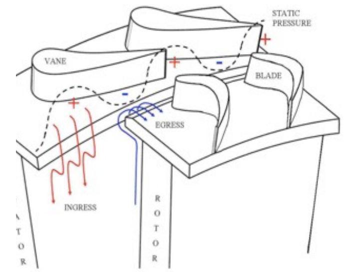
Fundamentals:

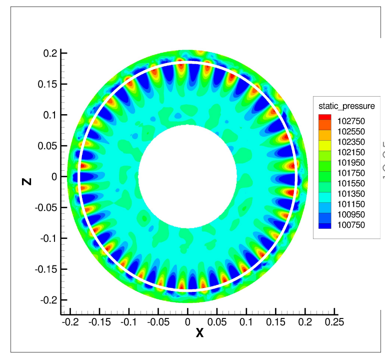
- Revisit $T_{adiabatic}$ on its physical meaning & how to measure.
- Scaling lab to engine conditions: (1) high heating loads (T_w/T_b bear 1 in labs to T_w/T_b up to 2 in engines) and (2) rotation

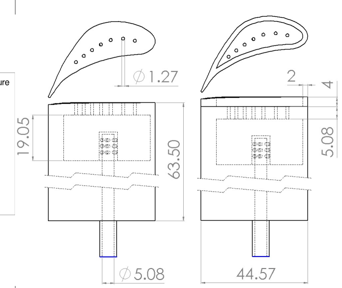
Applications:

- Study ingress/egress through rim seals via RANS & LES.
- Study blade-tip leakage in a 1.5 stage turbine with different blade tip treatment under lab and engine-relevant conditions, high- and low-load conditions via LES and VLES.
- Study internal cooling w and w/o rotation for scaling.
- Explore advanced concepts (e.g., microgap flow boiling).
- Develop & assess a new film-cooling designs (downstream vortex generators, Y-shaped hole) with NETL.
- Study NETL high temperature tunnel and its diagnostics with NETL.

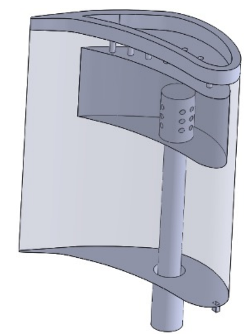
RIM SEALS: Bath and Aachen test rigs:
- rotation only
- rotation + vanes
- rotation + vanes & blades

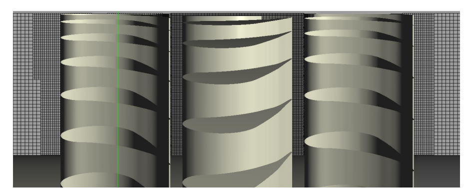






BLADE TIP in 1.5 stage: flat, squealer, … w/ and w/o film cooling





Quantifying and Scaling Effects of High Heat Loads on Heat Transfer

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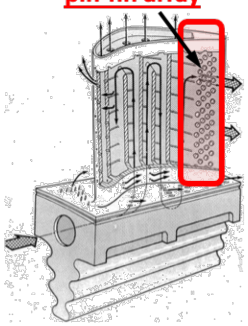
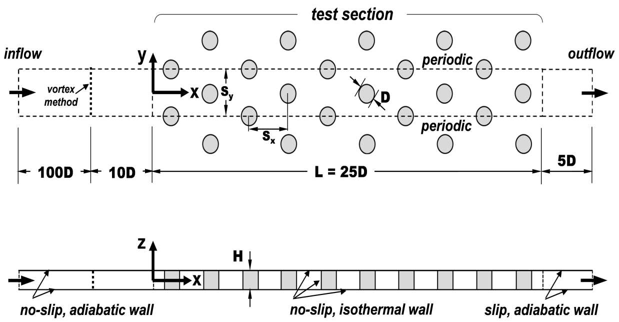
K. Mark Bryden
Ames Laboratory, Department of Energy

Effects of High Heat Loads on Flow & Heat Transfer in Cooling Passages with Pin Fins:
Entrance Region + Pin Fins and Endwall

trailing-edge cooling pin-fin array

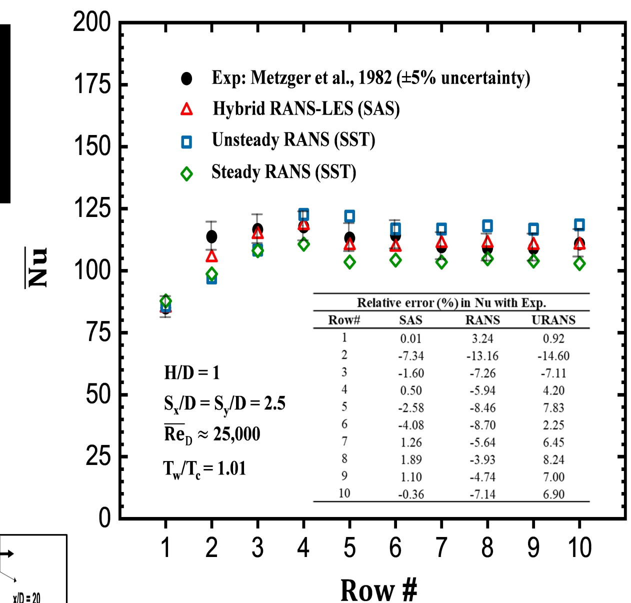




Cooling gas (air)

$\dot{m} = 0.00636$ kg/s
$T_c = 673$ K
$P_b = 25$ bars
$Re_{D,x/D=1.25}(\rho V_{max} D/\mu) = 25{,}000$

Case#	T_w (heat load)	T_w/T_c
1	678 K	1.01
2	873 K	1.30
3	1,073 K	1.60
4	1,273 K	1.90



Relative error (%) in Nu with Exp.			
Row#	SAS	RANS	URANS
1	0.01	3.24	0.92
2	-7.34	-13.16	-14.60
3	-1.60	-7.26	-7.11
4	0.50	-5.94	4.20
5	-2.58	-8.46	7.83
6	-4.08	-8.70	2.25
7	1.26	-5.64	6.45
8	1.89	-3.93	8.24
9	1.10	-4.74	7.00
10	-0.36	-7.14	6.90

Problem Formulation:

- Gas: compressible, thermally perfect gas with k(T), C_p(T), and μ(T)
- Turbulence: hybrid LES-RANS → Scale-Adaptive Simulation (SAS) model (Menter & Egorov, 2010)

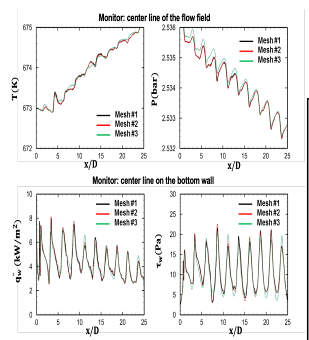
Code: ANSYS-Fluent v17.1

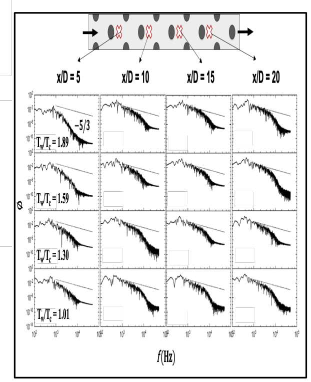
Algorithm:

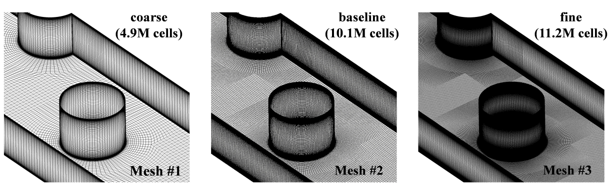
- 2nd-order accurate in time
- PISO with 2nd-order upwind for the advection terms & central for diffusion terms

Convergence Criteria for Unsteady Solutions:

iterate until converged at each time step (typically 20 to 30 iterations per time step) - normalized residual at the end of each time step for continuity< 10^{-5}, momentum< 10^{-5}, and energy<10^{-7}, turbulence quantities < 10^{-5}.



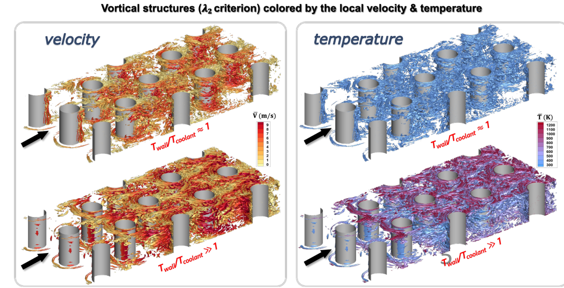




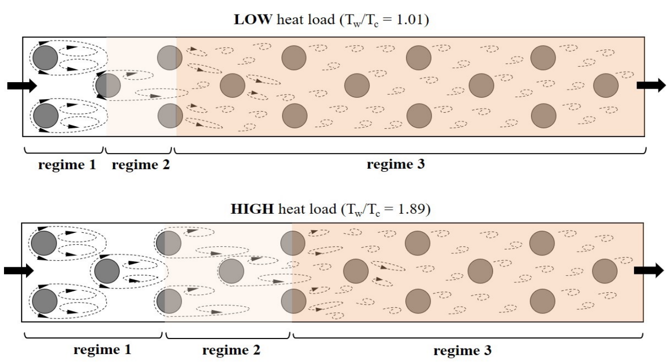
Index of resolution quality (Celik et al. 2005)

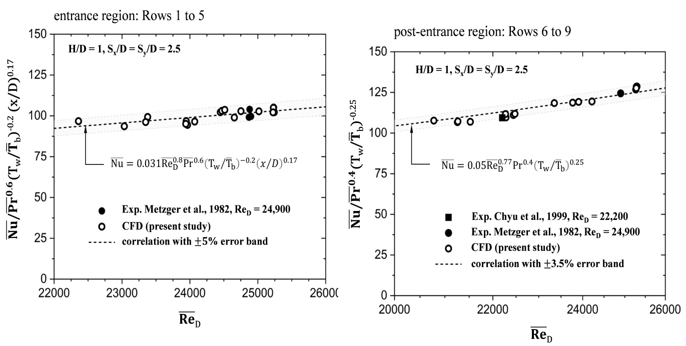
$$LESIQ_v = \frac{1}{1 + 0.05\left(\frac{\mu + \mu_{SGS}}{\mu}\right)^{0.53}} > 0.9$$

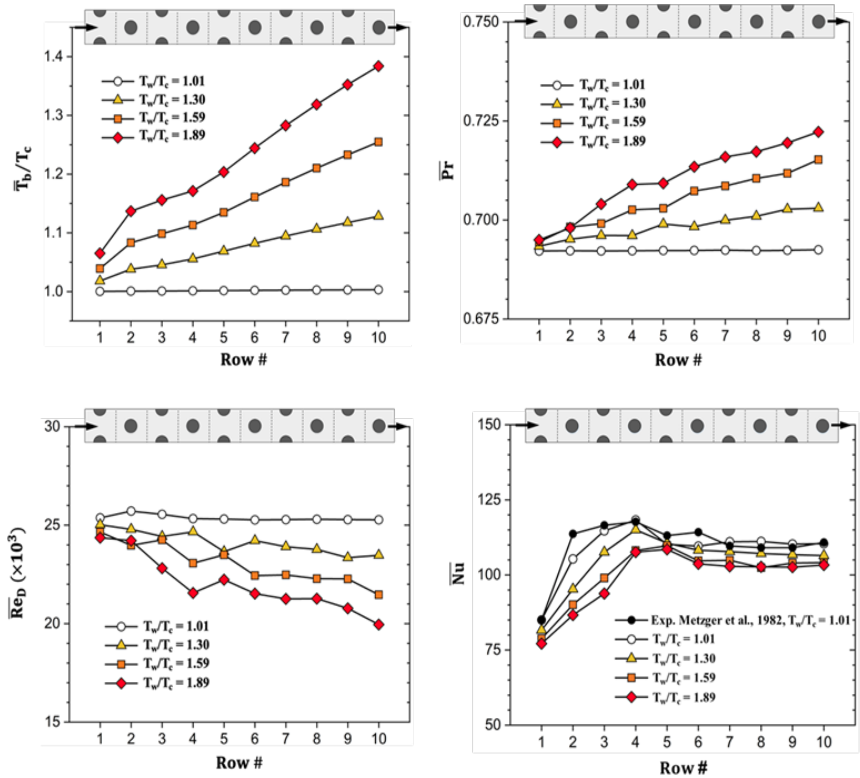
Vortical structures (λ_2 criterion) colored by the local velocity & temperature

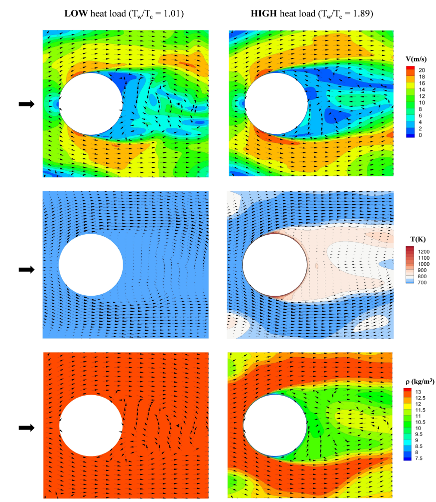


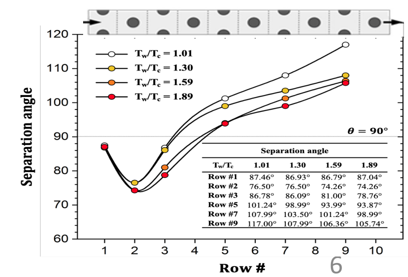
Lab vs Engine Conditions











Separation angle				
T_w/T_c	1.01	1.30	1.59	1.89
Row #1	87.46°	86.93°	86.79°	87.04°
Row #2	76.50°	76.50°	74.26°	74.26°
Row #3	86.78°	86.09°	81.00°	78.76°
Row #5	101.24°	98.99°	93.99°	93.87°
Row #7	107.99°	103.50°	101.24°	98.99°
Row #9	117.00°	107.99°	106.36°	105.74°

Thus, EFD & CFD need to work together.

Lee, C.-S. and Shih, T. I-P., "Effects of Heat Loads on Flow and Heat Transfer in the Entrance Region of a Cooling Duct with a Staggered Array of Pin Fins," *International Journal of Heat and Mass Transfer*," Vol. 175, 2021 (https://doi.org/10.1016/j.ijheatmasstransfer.2021.121302).

Adaptive Downstream RANS Model for Hybrid LES-RANS Methods

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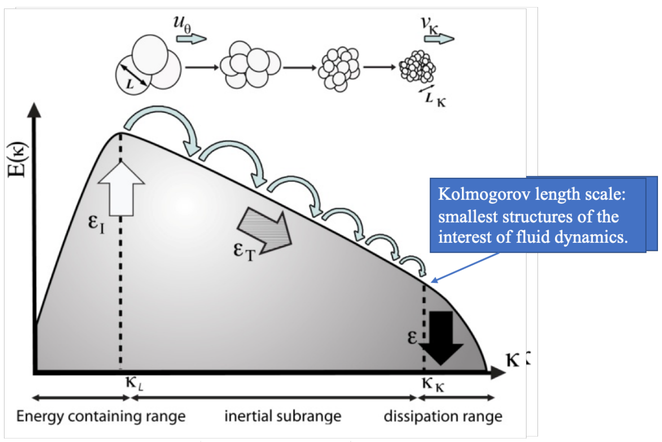
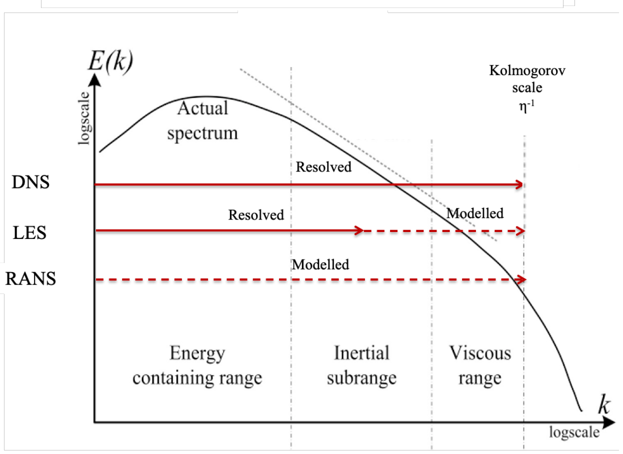
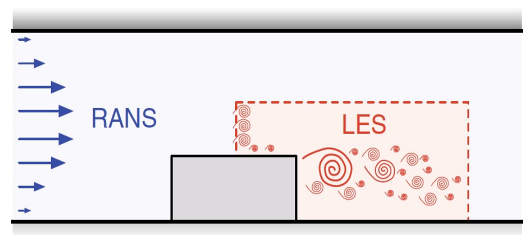
Turbulence and Its Modelling

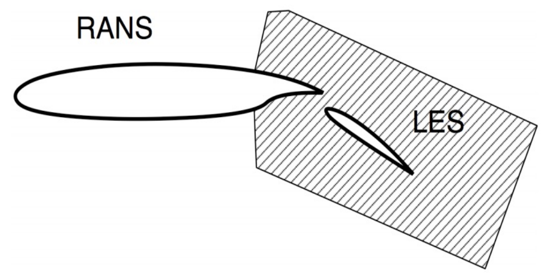
Energy spectrum of turbulent kinetic energy





Hybrid RANS- LES combines the advantages of LES and RANS to get accurate solutions more efficiently. Basically, LES is applied where RANS cannot provide physically meaningful results and RANS is applied where it could.





But, there are problems!

- Inflow BC to the LES region.
- Downstream RANS model cannot sustain the LES solution

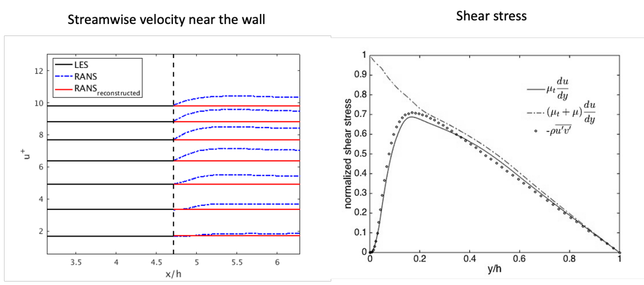
This study developed

- an anisotropic RANS model with Reynold stresses constructed from the LES solution at the LES-to-RANS interface by using the three momentum equations with a tensorial eddy viscosity.
- a method to modify the downstream RANS model from one with a scalar eddy viscosity to one with a tensorial eddy viscosity to sustain the upstream LES information in the downstream RANS region.

Adaptive Downstream Tensorial RANS Model

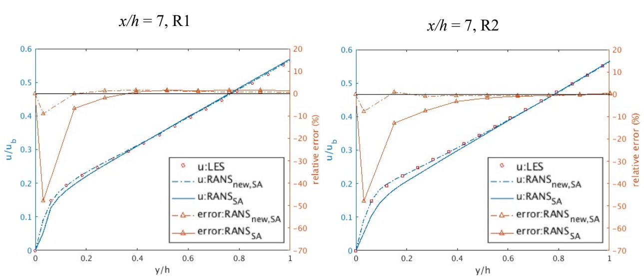
Channel flow

- The mismatch of the velocities between the LES-to-RANS interface near the wall is minimized after the reconstructed viscosity is used to rescale the RANS region.

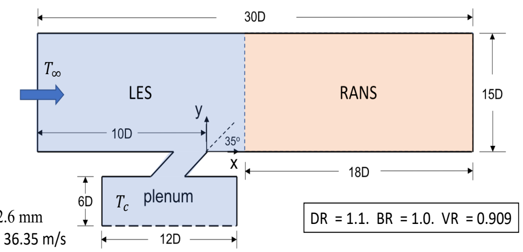


Periodic Hill Flow

- The propagation technique proposed in the new adaptive RANS model greatly reduces the difference between RANS and LES predictions downstream of the RANS/LES interface.
- With the new adaptive RANS model, it is less sensitive to the location of the RANS/LES interface.



Test Case: Film Cooling



DR = 1.1. BR = 1.0. VR = 0.909

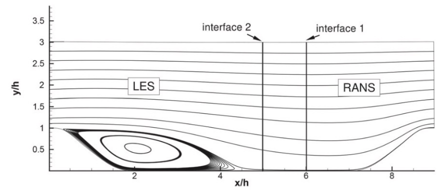
- D = 2.6 mm
- U_∞ = 36.35 m/s
- T_∞ = 297.3K
- T_c = 270.8K
- M = 0.1
- $Re = \rho U_\infty D/\mu$ = 6160
- B.C.s:
  Synthetic turbulent inlet B.C.;
  Pressure Outlet B.C.;
  Adiabatic no-slip walls;
  Periodic B.C. in spanwise direction;
  Mass flow rate inlet B.C. for plenum;

	LES	RANS
Code	HiFiLES	OpenFOAM
Model	WALE	NLEV-Adaptive
DoF/Mesh	14M	1M

Mesh size: pure LES ~1.6 times of the hybrid
CPU-hours: pure LES ~2.3 times of the hybrid.

- Zhang, W. and Shih, T.I-P., "Adaptive Downstream Tensorial Eddy Viscosity for Hybrid LES-RANS Simulations," *International Journal for Numerical Methods in Fluids*, Vol. 93, No. 6, June 2021, pp. 1825-1842 (DOI: 10.1002/fld.4954).

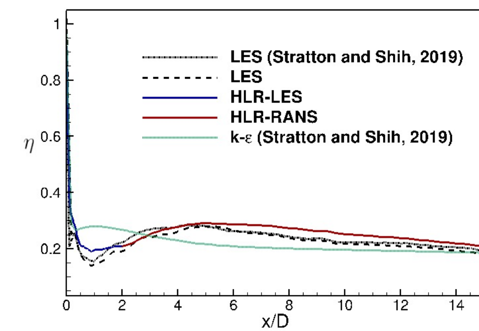
- A 2nd paper on film cooling is being written now.



Film Cooling

- **Adiabatic effectiveness at z/D=0**

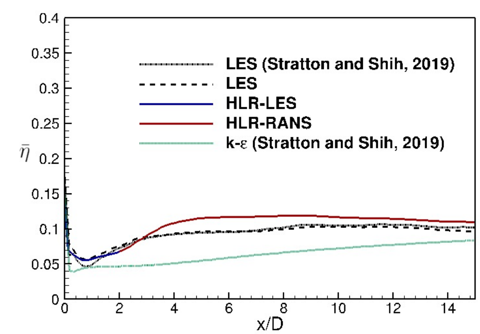
$$\eta = \frac{T_w - T_\infty}{T_c - T_\infty}$$



- The result of the Hybrid LES-RANS method (HLR) agrees well with the full LES case, with a little offset near the interface condition.

Film Cooling

- **Laterally-averaged adiabatic effectiveness**



- The Hybrid LES-RANS method (HLR) slightly overestimates the laterally-averaged adiabatic effectiveness and the $k-\varepsilon$ model underestimates it.

Experimental and Computational Analysis of Advanced Film-Cooling Configurations

Chien-Shing Lee, AJ Inanc, and Tom I-P. Shih
School of Aeronautics and Astronautics, Purdue University

Doug Straub, James Black, Justin Weber, Joseph Yip, and Edward Robey
National Energy Technology Laboratory, Department of Energy

How to Improve Film Cooling? Previous Work

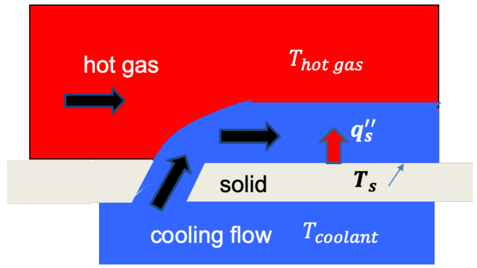
Design Concepts:

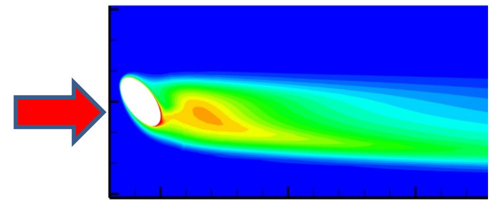
Make CRVs work for you!
- 2 staggered rows (Han & Mehendale
- slots
- 2 staggered rows of slots
- **flow-aligned blockers** (Shih, et al.)

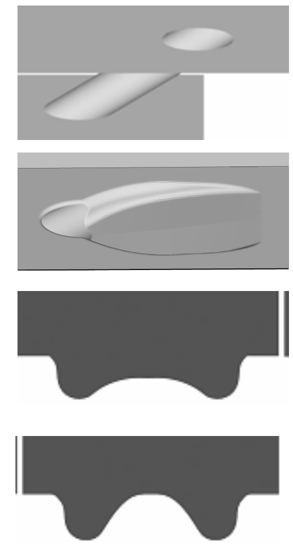
Change hole shape/orientation:
- **shaped holes** (Thole, Leylek, …, Shih)
- compound-angle holes (Goldstein, Ligrani, Bogard, …)
- transpiration cooling

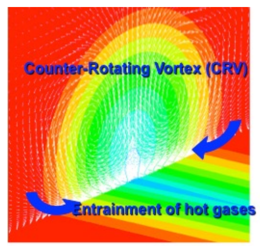
Change hot gas/cooling jet interaction:
- tabs about holes (Zaman & Foss)
- trench (Bunker, …, Shih)
- **upstream ramp** (Na & Shih)
- **ramp, ramp+blockers** (Na & Shih)

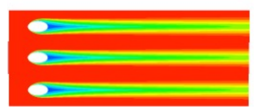
Anti-Kidney vortices:
- struts inside hole (shih)
- 2 side jets (Heidman, Ekkad)

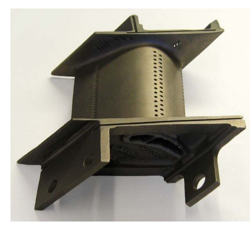


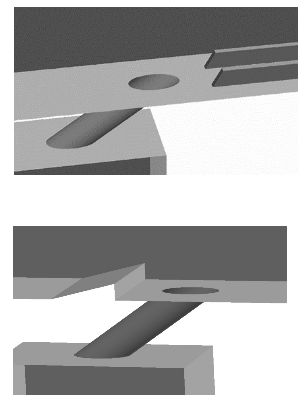


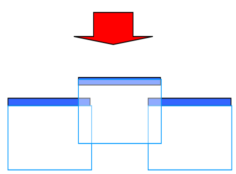


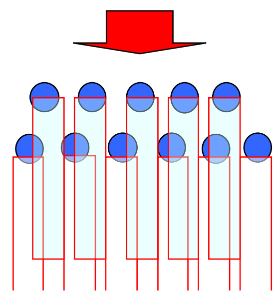


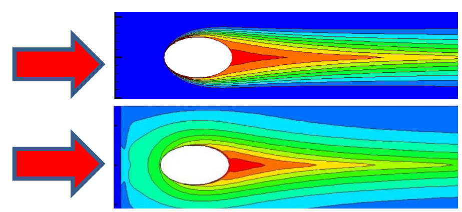


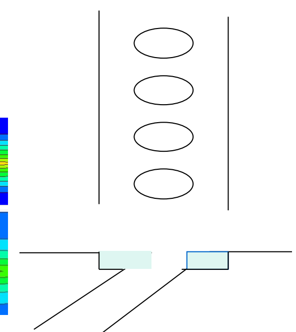






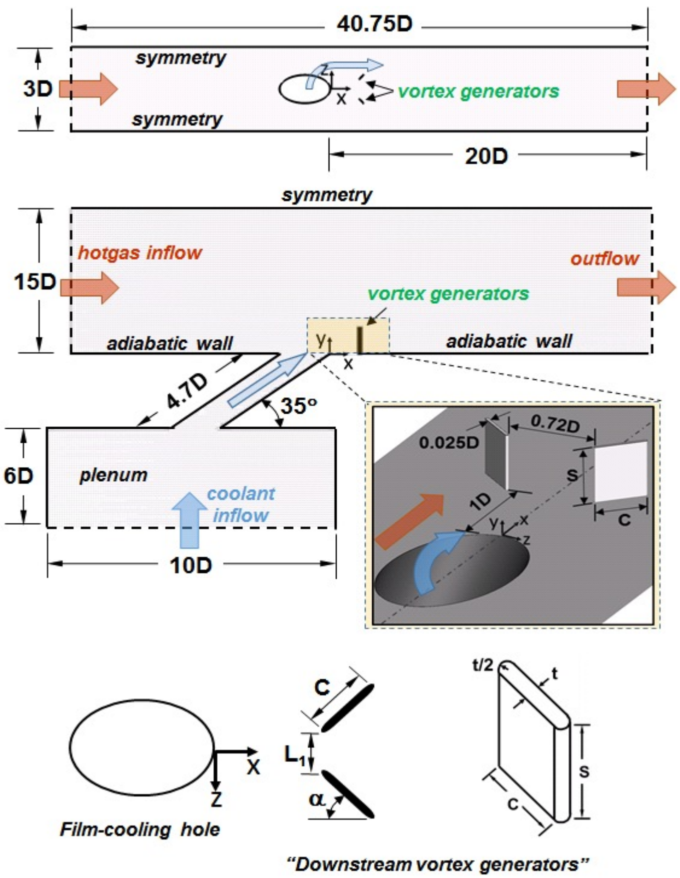


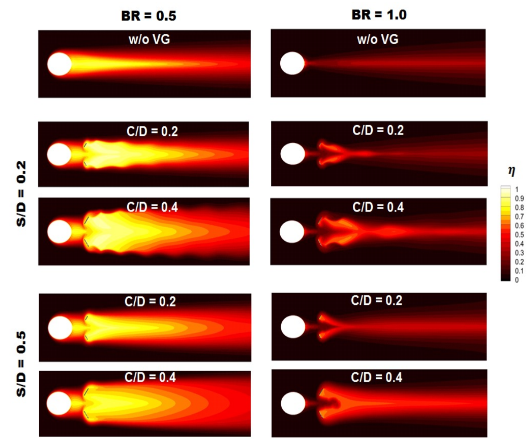


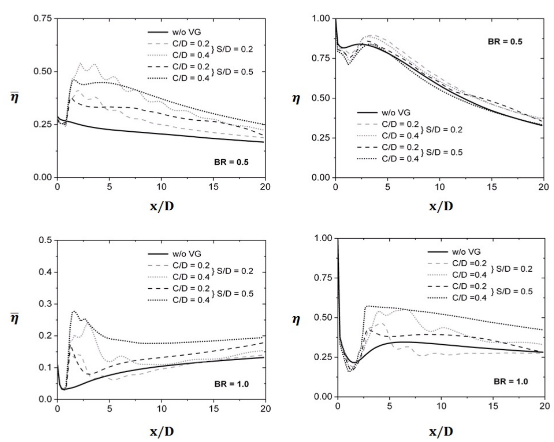


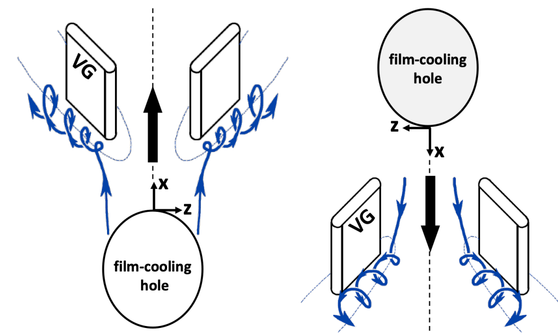
Our New Design: Downstream Vortex Generators (ASME GT-2020-14317)

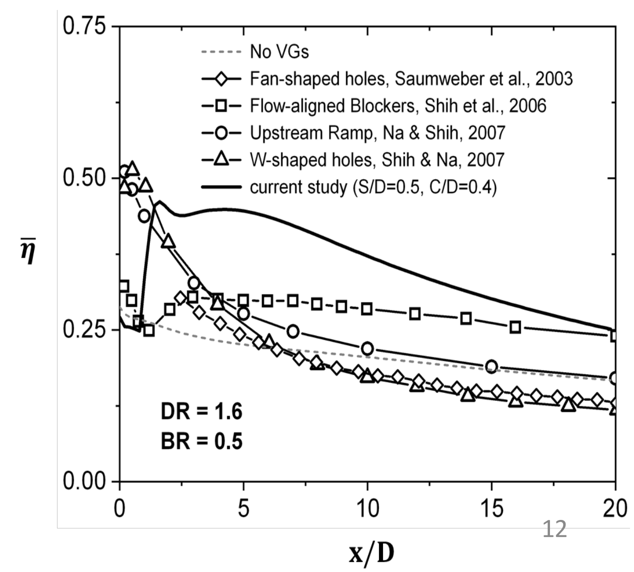
Lee, Bryden, & Shih, T.I-P., "Downstream Vortex Generators to Enhance Film-Cooling Effectiveness," ASME Paper GT2020-14317, 2020.





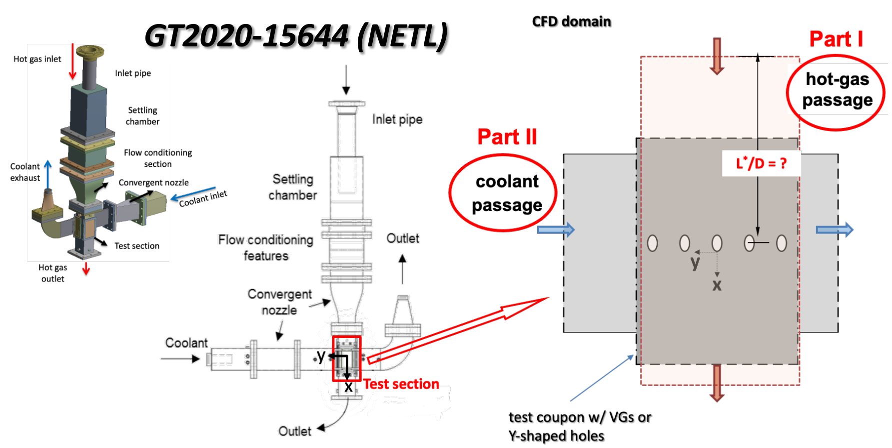


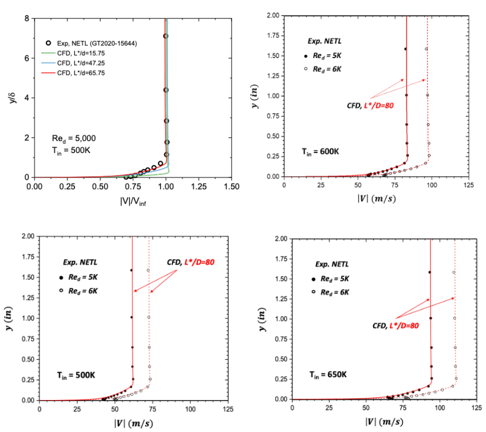


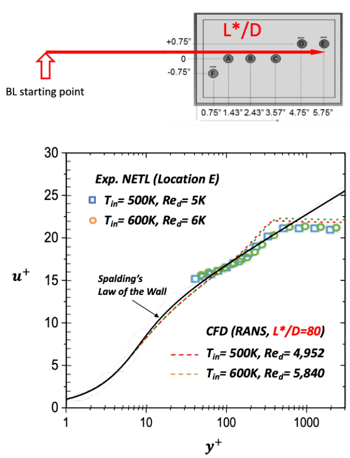


Conjugate RANS & LES at Purdue & Measurements at NETL Tunnel

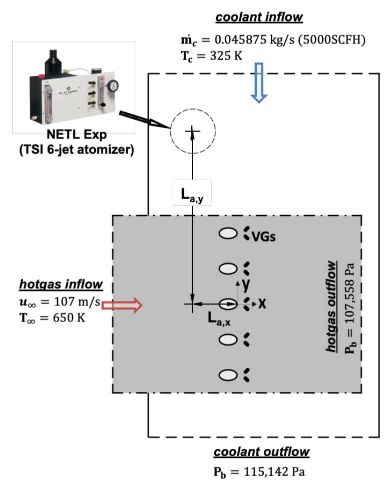
Cross Flow and a New Plenum

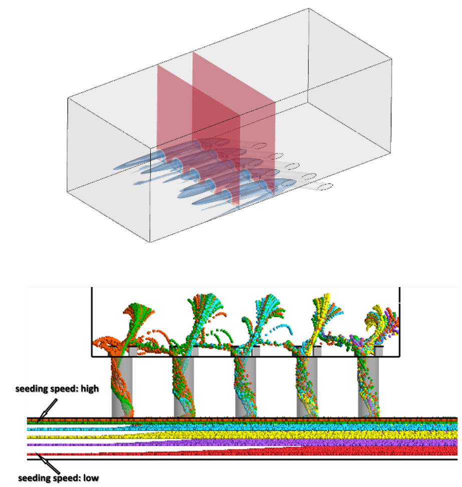




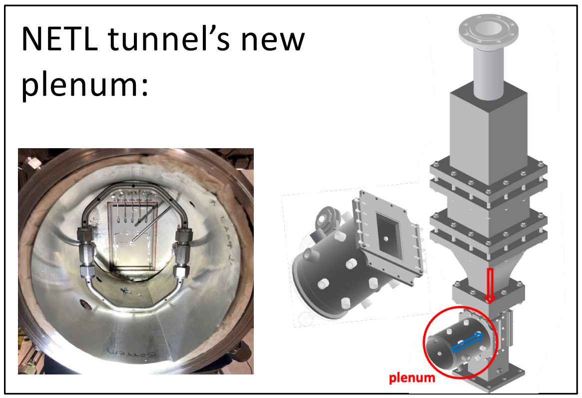


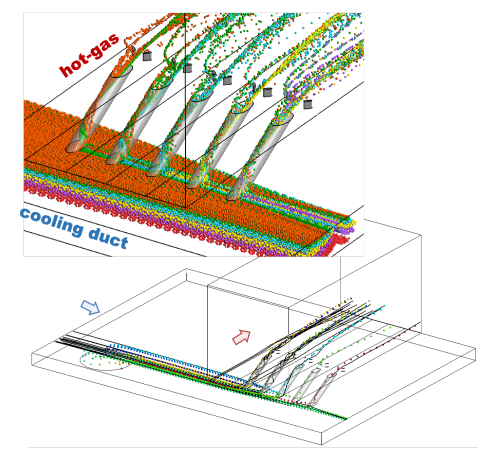
Assess Trajectories of Bubbles in Visualizing the Flow





NETL tunnel's new plenum:





The focus of our research is on the **thermal management** of gas turbines to increase efficiency and service life **with NG, NG with H_2, 100% H_2, and ammonia as fuel**.

Summary of Recent Efforts

Design and Analysis Tools:

- Developed a BCs for the LES-to-RANS interface in hybrid methods to ensure stability at the interface.
- Developed an adaptive RANS model with an anisotropic eddy viscosity that mimics the upstream LES solution so that the LES region can be reduced in size to increase computational efficiency.

Fundamentals:

- Showed LES is needed when computing flow and heat transfer about pin-fin arrays to capture correctly the onset of unsteady shedding and quantified how unsteady shedding affects time-averaged heat transfer.
- Showed how high heat loads affects surface heat transfer in a high-aspect ratio rectangular channel with a staggered array of short pin fins and and developed correlations for the Nusselt number in the entrance and the post-entrance regions.

Applications:

- Developed downstream vortex generators and Y-shaped holed to improve adiabatic effectiveness.
- Currently working with NETL on experimental validation of these two designs and examining how the flow in the internal cooling passage relative to the inclination of the film-cooling hole affect adiabatic effectiveness.

Thank you for your attention!

Comments? Questions?