PSEUDO-SPECTRAL METHOD FOR CONJUGATE HEAT TRANSFER PREDICTION OF IMPINGING FLOWS OVER ROUGH SURFACES

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Argonne National Laboratory
Muhsin Ameen, Saumil Patel, Nadish Saini*

Raytheon Technologies Research Center
Miad Yazdani

Acknowledgments

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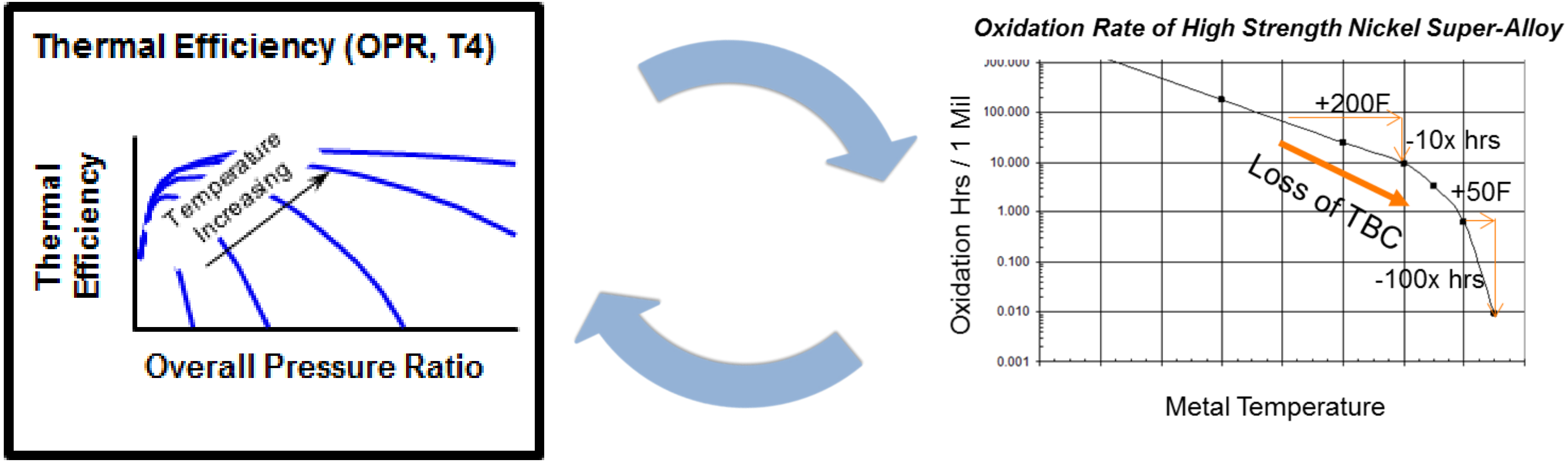
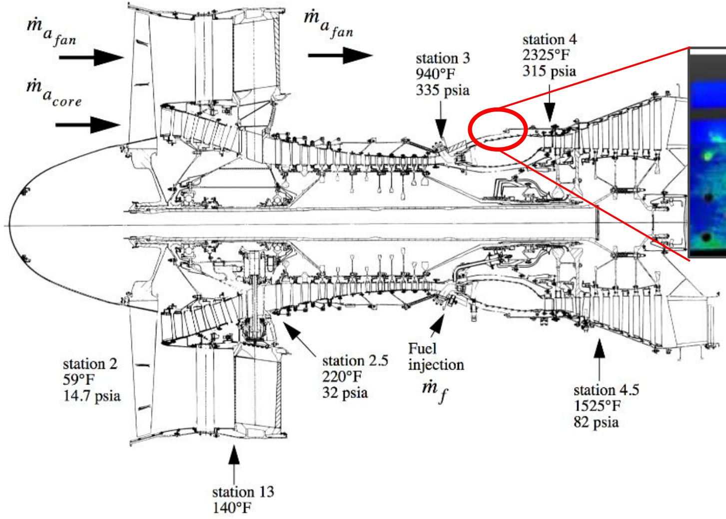
Motivation

- Future gas turbine concepts rely on operating at high pressure and temperature for improved thermal efficiency
  - Higher heat load on combustor liners → temperature reaches close to oxidation limit

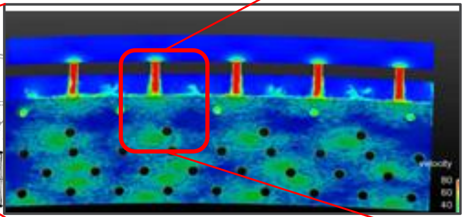


Motivation

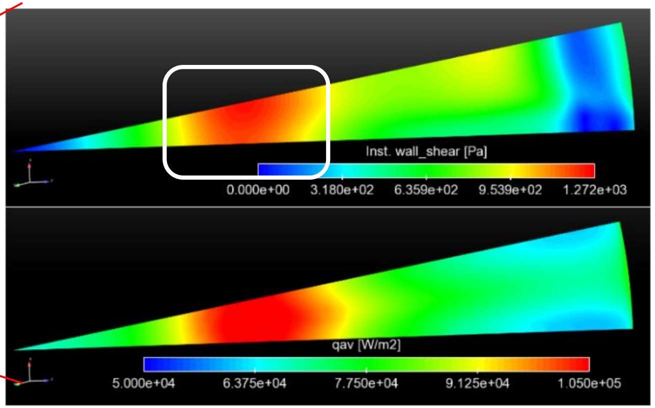
- Jet impingement-effusion cooling is an efficient method for removing heat from combustor liner's surface
  - Preliminary DNS simulations show a further enhancement of heat transfer coefficient (HTC) for a rough liner surface

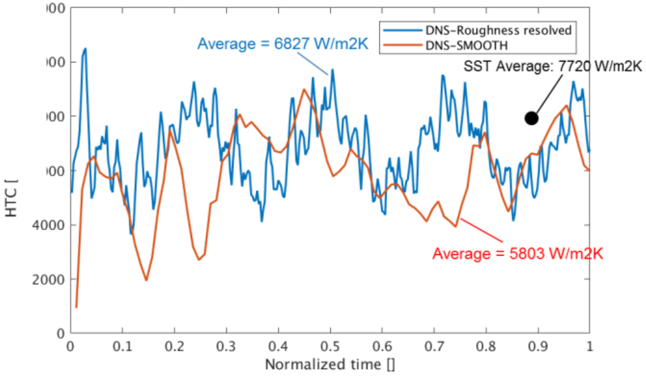


Gas Turbine Schematic



Combustor Liner



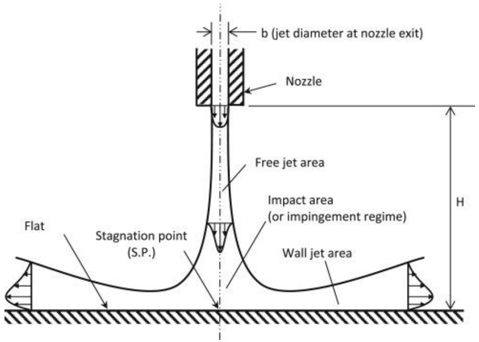


HTC for smooth and rough surfaces

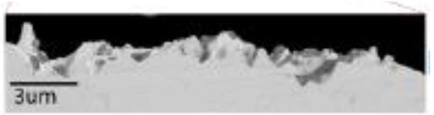
Scope/Objectives

- Develop a first-principles based simulation framework for predicting flow and heat transfer characteristics of jet impingement flow in gas turbine combustor liners with *resolved surface effects* to develop *advanced cooling concepts* for combustors to operate at higher pressures and temperatures
  – Understand the effect of manufacturing process on the heat transfer process
  – Develop reduced-order models that can account for the surface characteristics

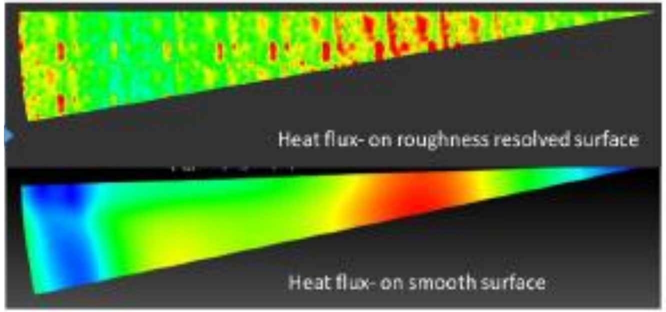
- This project combines the gas turbine combustion expertise at RTRC and computational modeling expertise and high-performance computing capabilities at DOE



Schematic of the simulation setup



Measured roughness profile for a typical combustion liner



Preliminary roughness resolved simulation by RTRC

Project Workflow - Jet Impingement Simulations

Validation Study	• Smooth wall simulation at $Re = 10k$ with constant heat flux BC • Validating velocity and Nusselt number profiles with published experimental and simulation data
Conjugate Heat Transfer	• CHT simulation with smooth interface • Similar flow condition as validation study • Constant heat flux applied at bottom wall of solid substrate
Characterization of Surface Roughness	• Measure roughness profile for a (typical) specific combustor liner using white light topography (RTRC)
Roughness Resolved Simulations	• Impose a regularized roughness profile at the solid-fluid interface • High-fidelity simulations with conditions similar as the smooth CHT case • Characterize effects of roughness on heat flux distribution and Nusselt number

Parametric Simulations	• Perform simulations for:
	  • Different surface roughness topologies
	  • Different Reynolds number

Further Analysis	• Data regression to develop subgrid models for URANS tools to improve their heat transfer prediction capability • Heat transfer characterization of surfaces fabricated using different manufacturing techniques

NekRS – GPU Accelerated CFD Solver

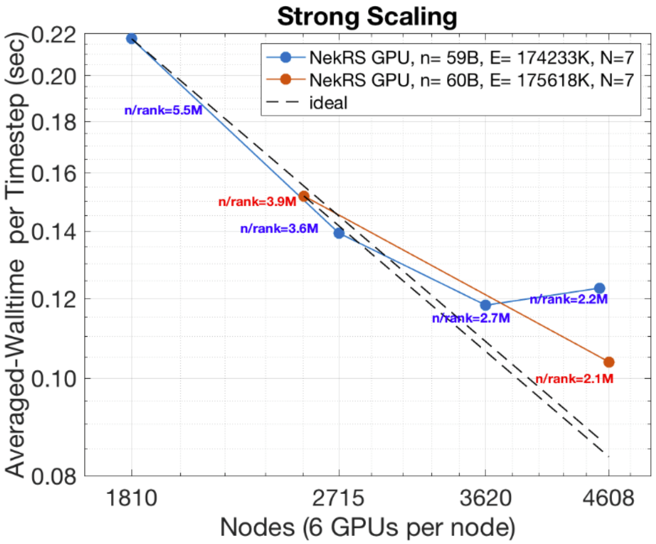
- NekRS code is based on high-order spectral element method (SEM) spatial discretization

- **Features:**
  - High-order leads to exponential convergence.
  - Excellent transport properties
  - Proven high scalability on up to 10^6 processors.
  - Ability to model incompressible/low-Mach flows
  - Handle complex geometries with moving boundaries
  - Integrated conjugate heat transfer modeling capability

- Nek5000: CPU (legacy) version

- NekRS: GPU-accelerated version of Nek5000 developed as part of DOE Exascale Computing Project (ECP)

- All simulations in this project run on the Summit supercomputer at Oak Ridge National Lab (ORNL) – secured 50k node hours using a DD allocation

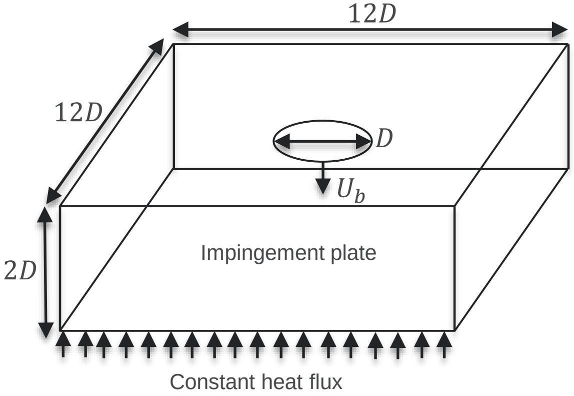


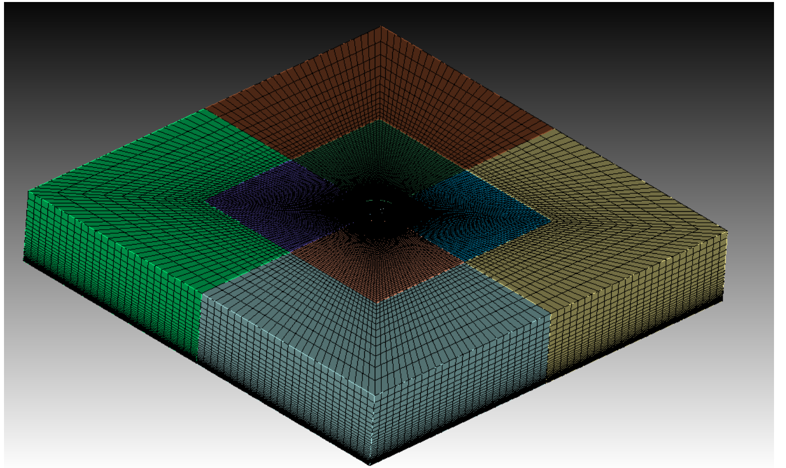
NekRS strong scaling for a full-core reactor mesh (E = 174,233,000) on Summit supercomputer.

Fischer, P., Kerkemeier, S., Min, M., Lan, Y. H., Phillips, M., Rathnayake, T., ... & Warburton, T. (2021). NekRS, a GPU-Accelerated Spectral Element Navier-Stokes Solver.

DNS of Impinging Jet

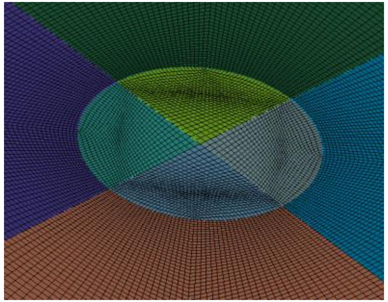
- Jet impingement on a surface with constant heat flux boundary condition – Dairay et al, 2015
  - $Re = 10000$





- Mesh specifications:

Element Count	756,704
Total $dofs$	387.43M (7[th] order basis)
Near wall mesh resolution	$\Delta y_w^+ = 0.94; \Delta y_w = 0.001D$
(Radial) Resolution near jet inlet	$\Delta r = 1.32; \Delta r = 0.0014D$



Note: Internal GLL nodes not shown

Dairay, T., Fortuné, V., Lamballais, E., & Brizzi, L. E. (2015). Journal of Fluid Mechanics, 764, 362.

Simulation Setup

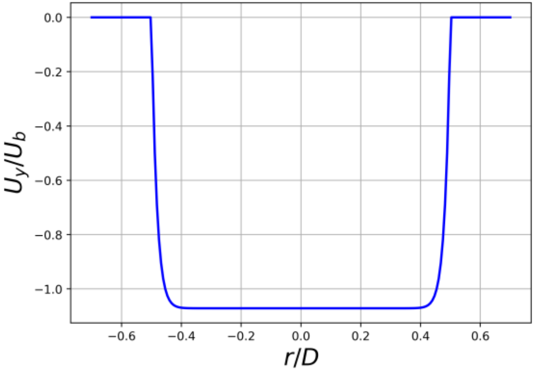
- **Inflow Conditions**

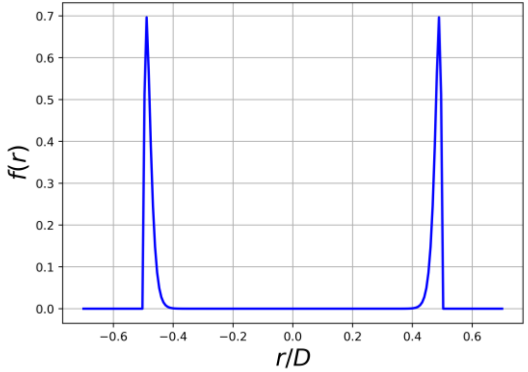
$$Mean\ inflow \rightarrow U_y = -\frac{n+2}{n}\left(1 - \left(\frac{2r}{D}\right)^n\right)U_b$$

  – Perturbations imposed on all velocity components

$$u' = f(r)\sum_{m=1}^{N} A_m(t)\cos\left(m\theta\ + \phi_m(t)\right)$$

    • $f(r) \rightarrow$ modulation function adjusted based on experimental conditions by Dairay et al (2014)
    • $A_m, \phi_m \rightarrow$ amplitude and phase generated randomly





- **Outflow Conditions**
  – Fringe method, Nordstrom et al (1999) → dampens flow perturbations
  – Body force added only in the "fringe region" (near the outlet)

$$\vec{F} = \lambda(r)(\vec{u}_o - \vec{u});\quad \lambda(r) = \frac{1}{2}(1 + \tanh(\beta(r - 5D) - 4D)\ )$$

  – Poiseuille flow (Dirichlet BC) imposed at the outlets

$$\vec{u}_o = \frac{3}{16}\frac{U_b D^2}{L_y r}\left(1 - \frac{4\left(y - (0.5L_y)^2\right)}{L_y^2}\right)\vec{e_r}$$

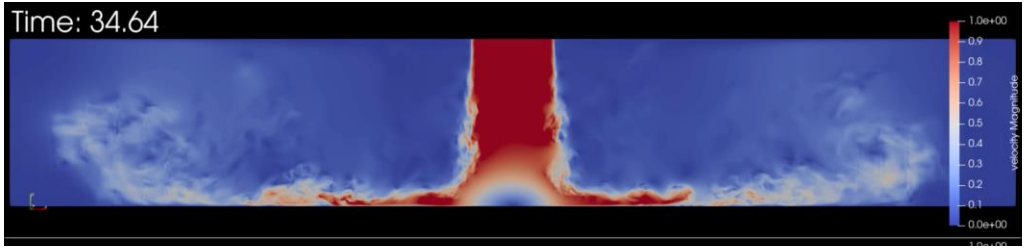
Ensures mass conservation

Does not conflict divergence free condition

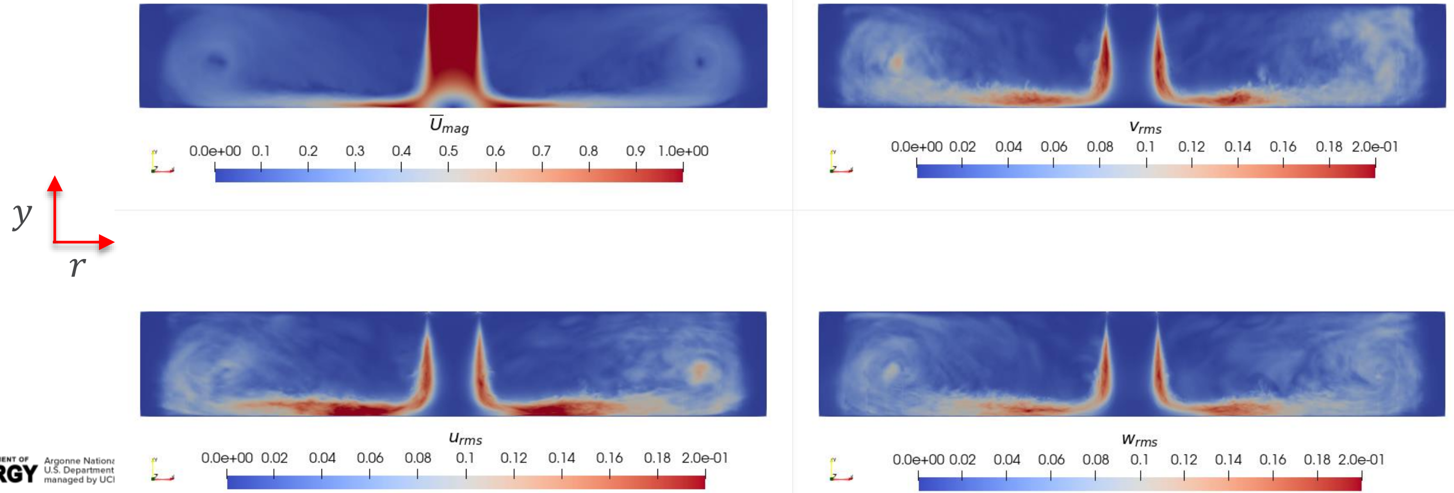
Nordström, J., Nordin, N., & Henningson, D. (1999). SIAM Journal on Scientific Computing, 20(4), 1365-1393.

Velocity Profiles (1/2)

- Instantaneous Profile:



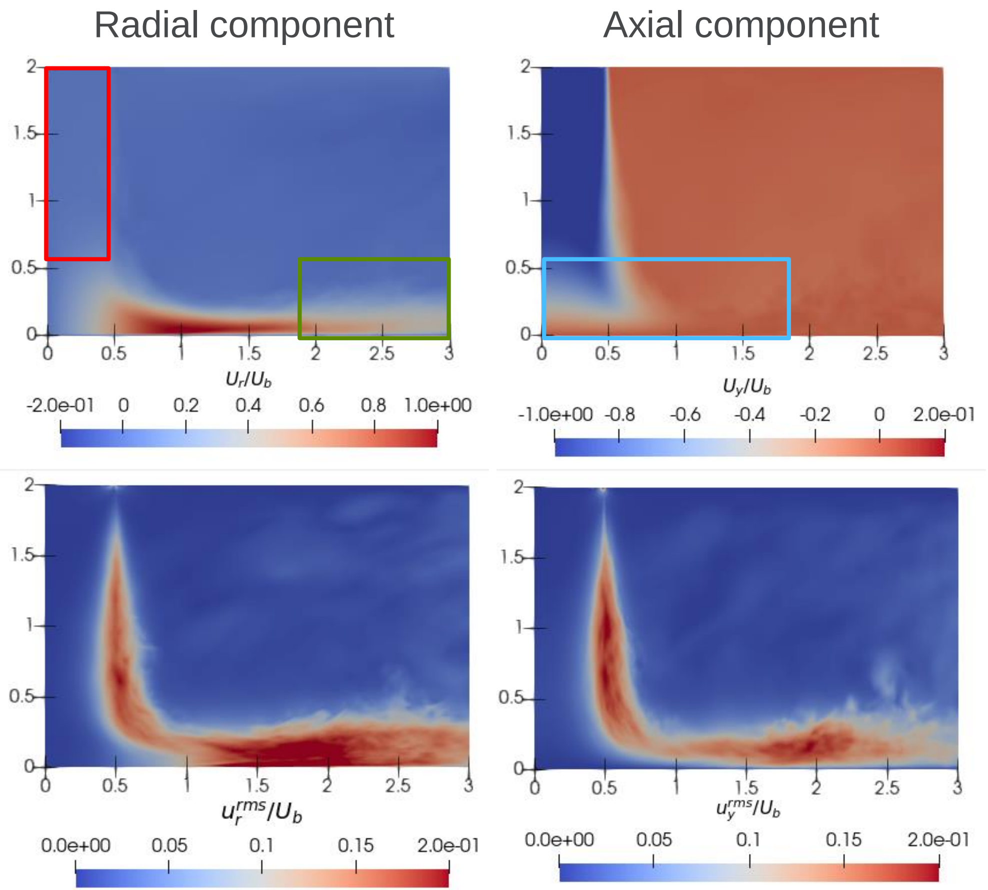
- Time averaged profiles



Velocity Profiles (2/2)

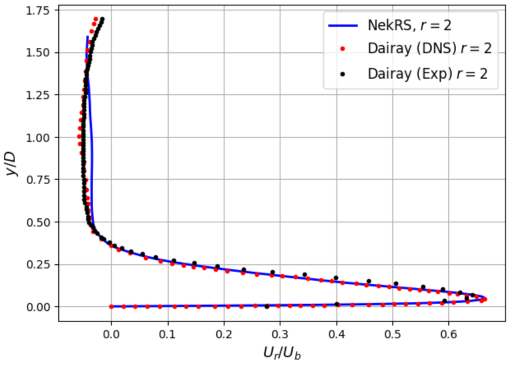
Primary regions of impinging jet flow are well captured:

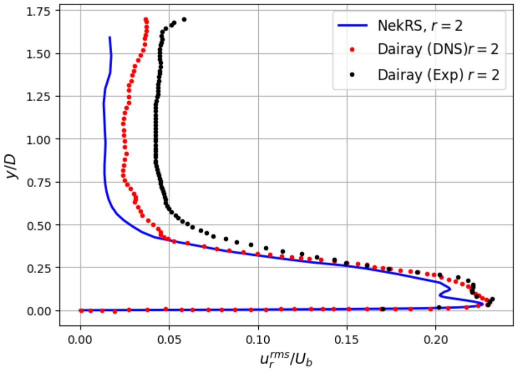
- Free jet region:
  - $r/D < 0.5, 0.6 < y/D < 2$
  - Primarily axial flow
  - Fluctuations do not exceed $0.05U_b$ in the core
- Stagnation region
  - $r/D < 1.8, 0 < y/D < 0.6$
  - Axial to radial flow orientation
  - Wall jet flow development, $r/D < 1$
  - Max fluctuations in this region
- Wall-jet region
  - $r/D > 1.8$
  - Fluctuations dampen
  - Primarily radial flow

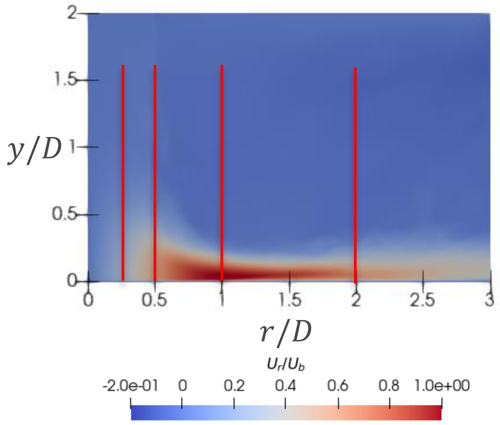


Validation of Velocity Profile

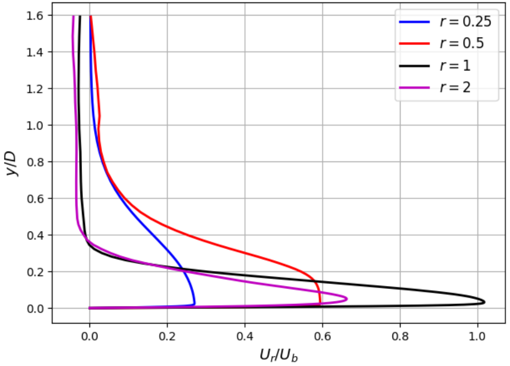
- Radial component of velocity (mean and rms) @ $r/D = 2$

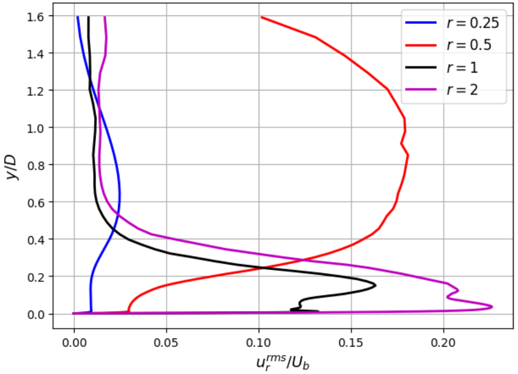






- Comparison of radial component at different radii locations

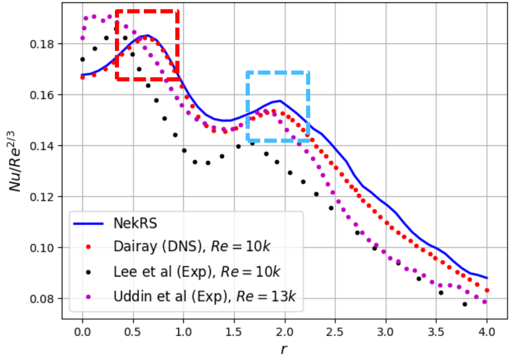


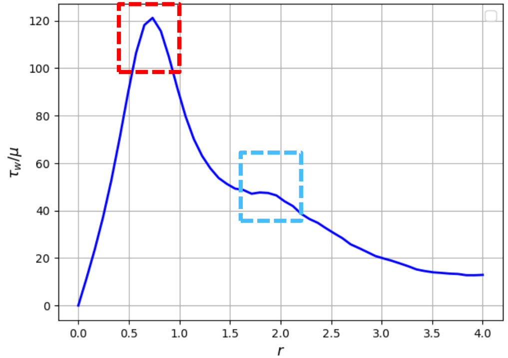


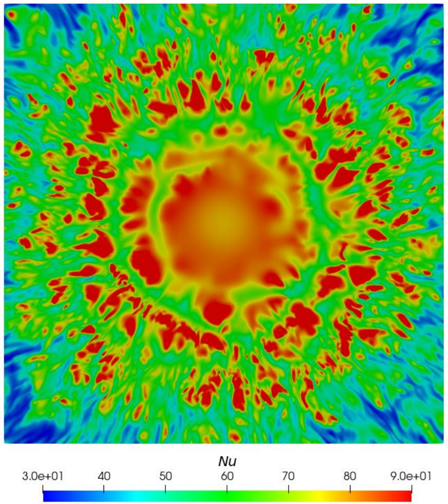
- Max radial velocity at $r/D = 1$
- Fluctuations peak near $r/D = 2$
  - Local maxima for Nusselt number

Nusselt Number Distribution

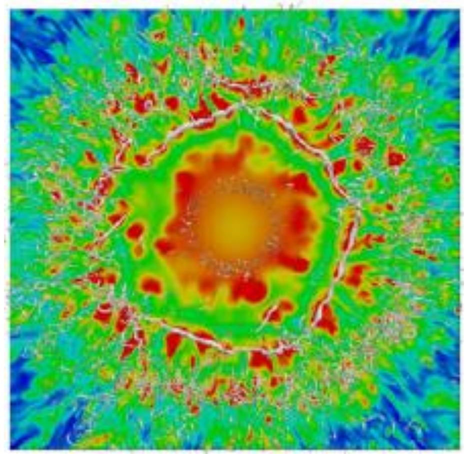
- Primary peak at $r/D \approx 0.7$ corresponds to peak in wall shear
- Local minima at $r/D \approx 1.3$ corresponds to stagnation point
- A secondary peak in the Nusselt number at $r/D \approx 2$ is reported in prior experimental literature (cannot be captured by RANS) → secondary vortices







Map of instantaneous Nusselt number on the impingement plate. Plate shown for the region $x/D, z/D = [-3,3]$



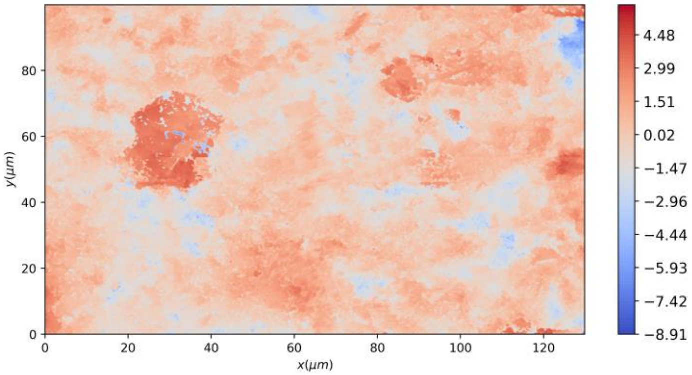
Nusselt number instantaneous contour reported by Dairay et al (2015)

Incorporating Surface Roughness (1/2)

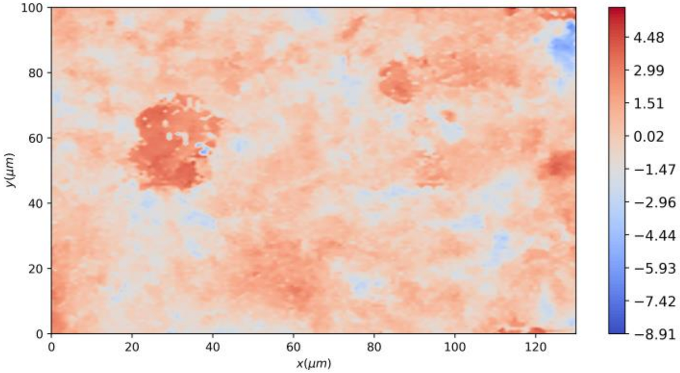
- Roughness measurements by RTRC using white light topography
  - Sample measurement for $130 \times 100\mu m$
- Fitting methodology
  - Data divided into uniform wafers of suitable length, say $1\mu m$
  - M^{th} order 2D spectral element basis used to fit data on each wafer using least squares regression
  - Fit obtained from all individual wafer elements, e_w, are combined to get roughness specification, ϕ, for the entire domain

$$\phi = \cup\, \phi_{e_w}; \quad \phi_{e_w}(\xi_1, \xi_2) = \sum_i \sum_j \psi_{ij}\, \pi_{M,i}\,(\xi_1) \pi_{M,j}(\xi_2)$$

ψ_{ij} → coefficients from least squares fit
$\pi_{M,i}$ → (1D) Lagrangian interpolant of degree M
(ξ_1, ξ_2) → coordinates of 2D reference element



Original data



Reconstructed roughness profile
130×100 5th order (spectral basis) 2D wafer mesh

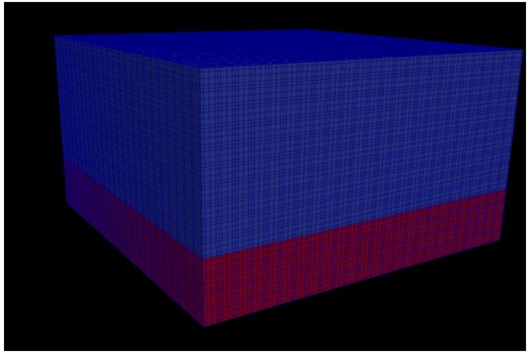
Incorporating Surface Roughness (2/2)

- Reading roughness data into **NekRS mesh**
  - Obtain the roughness elevation (stored as scalar, $\bar{\phi}$) at the GLL location by expansion using spectral basis coefficients, ψ, from wafer mesh
  - Translate NekRS coordinates vertically (assuming wall is at $y = 0$)

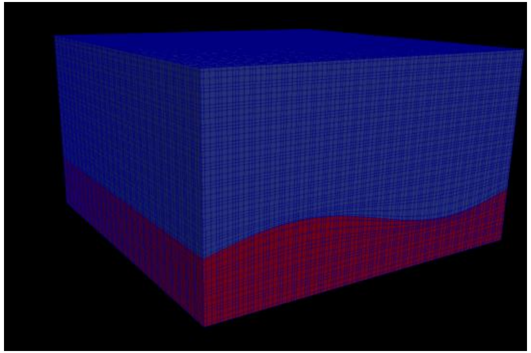
$$y(\xi_1, \xi_2) = y(\xi_1, \xi_2) + \bar{\phi}(\xi_1, \xi_2)\left(1 - \tanh\left(\frac{\kappa\pi y(\xi_1, \xi_2)}{abs(y_{min})}\right)\right)$$

    - κ is a regularization parameter. Adjusted to asymptote mesh translation to zero as $y \rightarrow y_{min}$

  - Example of mesh deformation at interface (work underway to transform mesh with actual roughness data)



Mesh with smooth fluid-solid interface



Deformed mesh; arbitrary roughness

Future Work

- Ongoing efforts for CHT simulation with smooth wall interface
- Extended roughness measurement effort for combustor liners are underway
  - Workflow for imposing roughness on NekRS meshes is established
  - Impending rough wall simulations
- Parametric studies with different roughness and/or turbulent inflow conditions
- Data regression to develop subgrid models for wall shear stress and heat transfer coefficients for smooth and rough walls
- Analysis of different manufacturing techniques for combustor liners for efficient heat transfer

Thank You!

Muhsin Ameen: mameen@anl.gov