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

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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
# 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.
**DNS of Impinging Jet**

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

- Mesh specifications:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element Count</td>
<td>756,704</td>
</tr>
<tr>
<td>Total $dofs$</td>
<td>387.43M (7th order basis)</td>
</tr>
<tr>
<td>Near wall mesh resolution</td>
<td>$\Delta y_{w}^+ = 0.94; \Delta y_w = 0.001D$</td>
</tr>
<tr>
<td>(Radial) Resolution near jet inlet</td>
<td>$\Delta r = 1.32; \Delta r = 0.0014D$</td>
</tr>
</tbody>
</table>

Note: Internal GLL nodes not shown

Simulation Setup

- **Inflow Conditions**
  
  Mean inflow → \( U_y = -\frac{n + 2}{n} \left( 1 - \left(\frac{2r}{D}\right)^n \right) U_b \)
  
  - Perturbations imposed on all velocity components
    
    \( \frac{\partial u^\prime}{\partial r} \rightarrow \text{modulation function adjusted based on experimental conditions by Dairay et al (2014)} \)
    
    \( A_m, \phi_m \rightarrow \text{amplitude and phase generated randomly} \)

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

    Ensures mass conservation

    Does not conflict divergence free condition
Velocity Profiles (1/2)

- Instantaneous Profile:

- Time averaged profiles

\[ \begin{align*}
\text{Instantaneous Profile:} \\
\text{Time averaged profiles}
\end{align*} \]
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 0.05\( U_b \) 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, $\phi$, for the entire domain

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

$\psi_{ij}$ → coefficients from least squares fit

$\pi_{M,i}$ → (1D) Lagrangian interpolant of degree $M$

$(\xi_1, \xi_2)$ → coordinates of 2D reference element
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, $\psi$, from wafer mesh
  
  - Translate NekRS coordinates vertically (assuming wall is at $y = 0$)

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

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

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

![Mesh with smooth fluid-solid interface](Image1)

![Deformed mesh; arbitrary roughness](Image2)
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!

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