LES and RANS/DERM Modeling for Design Optimization of Additively and Conventionally Manufactured Internal Turbine Cooling Passages

Annual Research Progress Report

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UTSR Program Review
17 November 2020
Contents

• Brief recall of background/objectives/technical approach/earlier progress
• Current activities and progress:
  • RIFT testing – heat transfer measurement focus
  • DERM model development/applications
  • DNS/LES/RANS tools, modeling, parameterizations
• Students and publications
• Summary and current/next steps
Background/Objectives/Technical Approach

• Metal AM enabling gas turbine design exploration of cooling schemes not currently manufacturable
• Potential *transformational* turbine operating temperature, durability gains
• **Need to mature thermal design tools**
  • Very complex “roughness field” that invariably characterizes flow passages
  • Conventional area parametrized roughness modeling for CFD inadequate
• Discrete Element Roughness Modeling (DERM)
  • *Necessary and sufficient* for mechanistic predictions of additively manufactured turbine cooling scheme configurations
  • Viable design approach for conventionally manufactured blade cooling features
Background/Objectives/Technical Approach

• Synthesis of state-of-the technology:
  • CFD modeling (DNS/LES/RANS) and optimization
  • Powdered metal additive manufacturing
  • Multiscale 3D scanning and attendant roughness field characterization
  • Flow/heat transfer measurements

• Deliver to turbine design community sufficiently physics rich, validated model set for design of cooling passages characterized by roughness morphology, tolerancing inherent to L-PBF manufacturing
  • Straightforwardly implemented within current OEM turbine design practice
  • 3D → far more general in breadth of applicability than Q1D
Design and build of surrogate L-PBF cooling passage geometries
- GE input
  - Coverage of geometry parameter space
- Cover build parameter space

Engine scale testing
- $\Delta p$ and q”
- PSU legacy data
- PSU new data
- GE data

100x scale testing at Baylor
- $\Delta p$ and q”
- Hotfilm and LDV
- As built and surrogate roughness morphologies

Multi-modal inspection
- CT, OP, SEM as necessary

Develop CAD suitable for scale-up, CFD mesh generation, and statistical characterization

DERM model development
- Formulation
- Morphology parameterization
- DNS calibration
- At scale and up scale calibration

Application and Optimization
Roughness and Internal Flow Tunnel

- Adiabatic work to date:
  - 50x or 100x geometric scale
  - Panels printed using FDM
  - Channel flow with two rough walls (86% of perimeter)
  - Bulk pressure loss measurements
  - Single wire and X-array anemometry
Roughness and Internal Flow Tunnel

- Adiabatic work to date:
  - 8 upscaled engine scale START configurations
  - 2 surrogate analog configurations
Heat Transfer Measurements

- Started late 2019 to date
Heat Transfer Measurements

- IR window and plates constructed
- Heat transfer plates etched & painted
- Flat black for the infrared emissivity
- Three rough surfaces
  - Inconel 718 upskin
  - Inconel 718 downskin
  - Hastelloy “Real_x102”
- Smooth surface for benchmarking
Results

- Prior measurements performed using additively manufactured (FDM) ABS plates
- HT plates machined from aluminum 6061 plates
- Do both methods produce the same roughness?
- Friction factor measurements
  - Good agreement
  - Aluminum to smooth acrylic has most significant difference (paint)
Surface Imaging

- RIFT Modified for HT Measurements
- IR Temperature Measurements
  - FLIR SC4000 on stand
  - IR viewing window
Results

• Nusselt Number Results
• Percentage Enhancement Results
Repeatability

• Six repeatability tests on Real-x102 Surface (Re = 30K, 40K)
• Overlapping uncertainty bars
Results

• Reynolds Analogy Performance Parameter
• Global Thermal Performance Parameter

\[
\left( \frac{\overline{Nu}}{Nu_0} \right) \left( \frac{f}{f_0} \right)^{1/3}
\]

Next Steps

• Use of V3V System (4-camera, tomographic PIV)

• Extruded aluminum frame for V3V system
  • Covid delayed
  • Import/trade issues with source country
  • Arrived Nov. 6

• Construction starts immediately!

• Start using soon with DEHS seeder

• TSI rep will visit early January to fully commission system and explore different seeding options
DERM model - review

- Volumetric vs. surface roughness parameterization
  - Draws on thinking from many researchers (Schlichting, Bons, Aupoix, McClain, Meteorology, Icing, Turbine heat transfer)
  - Approach here evolves from non-equilibrium 2-fluid modeling. Closure involves:
    - Statistical volume fraction representation of roughness morphology
    - Interfacial force modeling of (minimally) drag, spatial dispersion
    - Interfacial heat transfer and turbulence transport modeling
    - E.g.,

\[
\frac{\partial \alpha \rho u_i u_j}{\partial x_j} = \alpha \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \alpha (\mu + \mu_t) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - D_{u_i} + M_i
\]

\[
\frac{\partial \alpha \rho_0 u_i}{\partial x_j} = \text{viscous/turbulent diffusion} + \text{viscous work} + \text{interfacial heat transfer}
\]

\[
\frac{\partial \alpha \rho k u_j}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \alpha \left( \mu + \frac{\mu_t}{Pr_k} \right) \left( \frac{\partial k}{\partial x_j} \right) \right] + P - \alpha \epsilon + \text{Other terms}
\]
**DERM model motivation**

- Orders of magnitude reduction in CPU compared to DNS, LES, Resolved RANS, IBM

### Approximate Grid Size and Relative CPU Time Per Element @ $\text{Re}_\tau=540$

<table>
<thead>
<tr>
<th>Method</th>
<th>Grid Requirements</th>
<th>Relative CPU Time</th>
<th>Meshing Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNS$^1$</td>
<td>$O(10^7)$</td>
<td>1.0</td>
<td>High</td>
</tr>
<tr>
<td>Sublayer resolved RANS$^2$</td>
<td>$O(10^6)$</td>
<td>$10^{-3}$</td>
<td>High</td>
</tr>
<tr>
<td>Immersed Boundary Method$^3$</td>
<td>$O(10^{4,5})$</td>
<td>$10^{-4,-5}$</td>
<td>Medium$^4$</td>
</tr>
<tr>
<td>DERM$^2$</td>
<td>$O(10^3)$</td>
<td>$10^{-6}$</td>
<td>Low$^5$</td>
</tr>
<tr>
<td>$k^+$ based parametrization</td>
<td>$O(10^3)$</td>
<td>$10^{-6}$</td>
<td>Low</td>
</tr>
</tbody>
</table>

$^4$Spatially precise element geometry is required for cut cell

$^5$Spatial distribution of volume fraction, $C_D, C_S$ required

$^1$Chan JFM 2015  $^2$Present  $^3$Estimate
DERM model development/application

- Surfaces studied/parametrized to date using combinations of DNS/LES/RANS/DERM:
  - 8 engine scale START configurations
  - Surrogate ellipsoid, elliptical cone surfaces
  - Sinusoidal
  - Cube arrays
    - Aligned and staggered
    - Range of coverage densities: <1% → 100%
  - Wedges (Han)
DNS/LES/RANS tools, modeling, parameterizations

- DERM implementation in research code NPHASE-PSU
  - Straightforward to implement within any code that has Eulerian 2-phase capability
  - Coarse mesh per $k^+$ RANS run with wall functions – roughness not resolved
  - Volume fraction and permeability tensor pre-processing per roughness morphology model - deterministic
- Drag model
- Spatial dispersion model*
- Turbulence amplification

* Xu, Altland, Yang, Kunz JFM 2020

**Non-deterministic** Need to be modelled per exact form (e.g., Aupoix [2016]), conventional drag modeling (e.g., per A’” and porous flow literature), “new” modeling for spatial dispersion

Modeling ↔ Calibration
DNS/LES/RANS tools, modeling, parameterizations

• Inherently challenging details include:
  • **Mesh size/roughness scale being part of model** (per Eulerian multiphase flow)
  • Designation of virtual origin
  • Variation of $C_D$, $C_S$ with distance from wall to match per-element $C_{D_{tot}}$, $C_{S_{tot}}$
  • Limiting behavior as sparsity $\Rightarrow$ 0 or 100%
  • Underlying RANS models can perform poorly for explicitly resolved roughness*
    $\Rightarrow$ so how to use for calibration?
  • Model coefficients:
    • Minimal number of coefficients
    • Minimal parameterization/empiricism, e.g., $C_D$, $C_S = f(Re, \text{geometric descriptors for particular element type})$

*Altland, Xu, Kunz, Yang JFE 2020
Current DERM Model Set

• Drag:
  • $D = \frac{C_D}{l} \alpha \rho |U|$, $C_D = f(\text{Re}, l, \text{roughness unit coverage density } = \lambda_p)$
  • E.g. $C_D \approx .45$ for cube arrays*

• Dispersion:
  • Exact term (cartesian streamwise momentum) $\frac{d((U-U_{xy})(W-W_{xy}))_{xy}}{dx}$
  • $M_{i,\text{disp}} = C_S \nabla \alpha |U|$
  • E.g., $C_S = .1\lambda_p \frac{\text{filter width}}{l}$, filter width = $\forall / \Delta x \Delta z$

*Yang, Xu, Huang, Ge JFM 2019
Current DERM Model Set

• Turbulence Amplification*
  \[
  \frac{\partial \alpha \rho k u_j}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \alpha \left( \mu + \frac{\mu_t}{Pr_k} \right) \left( \frac{\partial k}{\partial x_j} \right) \right] + P - \alpha \varepsilon + D |U|^2
  \]

Drag Production

• Fully instrumented for “large” cell size: \( \forall_{\text{cell}} \gg k^3, y \gg k \), and homogeneous roughness distributions

*Gillandt, Crowe ICMF'98
DERM Model

- Cube array roughness (aligned)
- Sinusoidal roughness (sublayer resolved)
DNS/LES/RANS tools, modeling, parameterizations

• In addition to DERM framework, we require DERM calibration

• Surfaces studied/parametrized to date using DNS, LES, RANS:
  • 8 engine scale START configurations
  • Surrogate ellipsoid, elliptical cone surfaces
  • Sinusoidal
  • Cube arrays
    • Aligned and staggered
    • Range of coverage densities: <1% → 100%
  • Wedges (Han)

• Building a matrix of EFD+DNS/LES/RANS aimed at DERM calibration

• Using in house and some open-lit DNS/LES/RANS
RANS modeling/parameterizations

- In-house RANS models of each of 8 RIFT configurations
  - Geometrically-resolved roughness
  - 60 million cells
  - Steady flow, third-order accurate in space
  - Spalart-Allmaras turbulence model
RANS modeling/parameterizations

- Cross-section of RIFT results from previous UTSR reviews and publications to date*

*GT2019-90931, GT2020-14809, APS-DFD 2018: M32.00002
RANS modeling/parameterizations

- In-house RANS and open-lit DNS models of sinusoidal pipe
RANS modeling/parameterizations

- In-house RANS and in-house DNS models of cube arrays*

*Xu, Altland, Yang, Kunz JFM 2020
Altland, Xu, Kunz, Yang JFE 2021
RANS modeling/parameterizations

- In-house RANS models of Han* wedges

*Han JHT 1991
Students on Project

• Sam Altland
  • Penn State, Mechanical Engineering, PhD, Expected Graduation December 2021
  • Passed PhD Candidacy Exam September 2019, course work complete, Comps in December 2020
  • Spent Summer 2018 and Summer 2019 at GE Global Research as an intern developing experimental protocols for additively manufactured passages.

• Emily Cinnamon
  • Baylor University, Mechanical Engineering, MS, Graduated May 2020
  • Thesis: “X-Wire Examination of Turbulent Internal Flow in Simulated Additively Manufactured Turbine Blade Cooling Channels”

• Gabriel Stafford
  • Baylor University, Mechanical Engineering, MS, Defended 10/29/20, Graduating December 2020
  • Thesis: “Convection Measurements in Scale Models of Additively Manufactured Turbine Blade Cooling Passages”

• Ryan Boldt
  • Baylor University, Mechanical Engineering, MS, Started July 2020
  • Topic: “Tomographic PIV Investigations of Flow in Scaled AM Turbine Blade Cooling Passages”
Publications to Date

APS-DFD 2018: M32.00002
Title: Direct Numerical Simulation of Additively and Conventionally Manufactured Internal Turbine Cooling Passages

ASME Paper Number: GT2019-90931
Title: Flow in a Scaled Turbine Blade Cooling Channel With Roughness due to Additive Manufacturing

ASME Paper Number: GT2020-14809
Title: Flow in a Simulated Turbine Blade Cooling Channel With Spatially Varying Roughness Caused by Additive Manufacturing Orientation. Accepted ASME Journal of Turbomachinery

Title: Flow over Closely Packed Cubical Roughness Revisions submitted Journal of Fluid Mechanics

APS-DFD 2020: 2020-000876
Title: Closure of Distributed Element Roughness Modeling for Deterministic Roughness Morphologies Using DNS

ASME Paper: GT2021
Title: Convection in Scaled Turbine Internal Cooling Passages with Additive Manufacturing Roughness Abstract Accepted, In preparation

Title: Modeling of Cube Array Roughness; RANS, LES and DNS In preparation Journal of Fluids Engineering
Recent Publications

GT2020-14809

FLOW IN A SIMULATED TURBINE BLADE COOLING CHANNEL WITH SPATIALLY VARYING ROUGHNESS CAUSED BY ADDITIVE MANUFACTURING ORIENTATION

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ABSTRACT

Because of the effects of gravity acting on the molten metal caused during the laser melting process, additionally manufactured surfaces are often observed to exhibit roughness characteristics different from those seen on surfaces that have been laser written for the same applications. The roughness observed in this work was observed to impact flow in a coolant channel with different packing density of cubes in aligned and staggered configurations using multiple turbulence models. This study aims to model the roughness of a surface caused by metal deposition in order to predict the effects of even irregular roughness on the flow (in a fraction of the surface area). In addition, with the growth of additive manufacturing technology, a viable solution to conventional manufacturing, there is active research in the characterization of how the roughness of an AM surface affects fracture and heat transfer.

NOMENCLATURE

$A_{eff}$ = effective cross-sectional area (in $\text{mm}^2$)
$A_{pp}$ = plateau area (top-face projected area)
$D$ = Law of the wall constant
$C_D$ = nozzle or Venturi discharge coefficient

GT2021-59684

Modeling of Cube Array Roughness; RANS, LES and DNS

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University Park, PA, 16802

Flow over arrays of cubes is a classic method for CFD modeling of real-world turbine boundary layers. While considerable effort has been made to investigate these flows using DNS and LES, the ability of turbulence-resolved RANS to predict the bulk flow phenomena of these systems is relatively unexplored. Here, RANS simulations are conducted on an array of different packing densities of cubes in aligned and staggered configurations using multiple turbulence models, including a RANS, LES, and DNS. This study aims to model the roughness of an AM surface caused by metal deposition in order to predict the effects of even irregular roughness on the flow (in a fraction of the surface area). In addition, with the growth of additive manufacturing technology, a viable solution to conventional manufacturing, there is active research in the characterization of how the roughness of an AM surface affects fracture and heat transfer.

NOMENCLATURE

$A_{eff}$ = effective cross-sectional area (in $\text{mm}^2$)

GT2021-59684

CONNECTION IN SCALED TURBINE INTERNAL COOLING PASSAGES WITH ADDITIVE MANUFACTURING ROUGHNESS

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ABSTRACT

Additive manufacturing processes, such as direct metal laser sintering (DMLS), enable creation of custom turbine cooling internal passages and systems. However, the DMLS method produces a significant amount of surface roughness. Previous studies have shown that the increased surface roughness can have a significant impact on the flow characteristics within the passage. This work aims to develop a numerical simulation approach that can accurately model the effects of additive manufactured roughness on flow in turbine internal cooling passages. This study examines the effect of additive manufactured roughness on flow in turbine internal cooling passages. The results indicate that the use of additive manufactured surfaces can significantly affect the flow characteristics within the passage. This study provides insights into the design of turbine cooling passages and the effects of surface roughness on flow, which is essential for the development of more efficient and reliable turbine engines.

NOMENCLATURE

$A_{eff}$ = effective cross-sectional area (in $\text{mm}^2$)
Summary and Current/next steps

• 13 months out from end of project (12/31/2021)

• Progress to date:
  • RIFT adiabatic
  • RIFT convection
  • DERM formulation development
  • DNS, LES, RANS for DERM calibration of numerous roughness morphologies
  • DERM calibration
Summary and Current/next steps

• DERM development is now focus
  • Adiabatic calibration
  • Heat transfer
• “Winding down” and publishing the EFD, DNS/LES/RANS elements
• Optimization (Task 4) will “compete” with DERM effort through end of current project