Validation of CFD Approach for Gas Turbine Internal Cooling Passage Heat Transfer Prediction

Daniel Wilde
Introduction to Turbine Cooling

- Turbine components are exposed to extreme temperatures
  - Power generation of turbine proportional to firing (turbine entry) temperature
  - Technologies to cool turbine blade at high temperatures of great interest
- Means of turbine cooling
  - Internal cooling:
    - Compressor bleed air directed through cavities or passages within blade
  - Insulation
    - Low conductivity ceramic coatings which separate blade metal from hot gaspath
    - Internal cooling flow exhausted at blade surface to form cool film
- Steady state temperature occurs when heat into the blade is balanced the heat removal

Internal cooling example
Courtesy NASA HOST documentation
Project Scope

• Objective:
  – Develop and validate a CFD approach for rotating internal cooling serpentine passages which captures all relevant physics
  – Demonstrate sensitivity of model to changes in operating point

• Approach
  – CFD model generated and evaluated for:
    • Mesh sensitivity
    • Boundary condition / assumption sensitivity
    • Turbulence model sensitivity
  – Various experimental data sets collected for validation
    • Comprehensive comparison of CFD results to experiment
    • Sensitivity of model to various physics investigated
Outline

• Discussion of Physics of internal cooling flow
  – Investigation of expected flow behavior

• Experimental Data selection
  – Introduction to experimental rig geometries and procedures
  – Description of available data and post-processing required to compare CFD results to experiment

• CFD model development
  – Model calibration to baseline experimental data

• CFD Results Validation
  – Simulation performed based on model development outcomes and validated against selected experimental data
Physics and Model Behavior: Straight Duct

- Flow through a square duct develops secondary flows in the corners.
  - Discovered by Nikuradse,
  - purely resultant of anisotropic turbulent stresses

- The ability to generate these is often a turbulence model benchmark
  - Case F-0111 from “Collaborative Testing of Turbulence Models”

- Linear eddy viscosity models are unable to generate these secondary flows.
Physics and Model Behavior: Turning Flow

- As the flow approaches the turn, Dean vortices are generated by centrifugal instabilities
- Pair of counter-rotating vortices develops
  - Operating points considered exhibit high Dean numbers
  - Flow is unstable and multiple solutions can exist
  - Unfavorable pressure gradient on the inner wall drives eventual separation
- The turbulence model should accurately capture the separation and reattachment points.

Steady, Non-Rotating Square Channel CFD Showing Dean Vortices; (top) view looking radially inward; (bottom) isometric showing projected vectors and secondary flows
Physics and Model Behavior: Turning Flow

- As the flow approaches the turn, Dean vortices are generated by centrifugal instabilities
- Pair of counter-rotating vortices develops
  - Operating points considered exhibit high Dean numbers
  - Flow is unstable and multiple solutions can exist
    Unfavorable pressure gradient on the inner wall drives eventual separation
- The turbulence model should accurately capture the separation and reattachment points.

Reynolds-stress model indicates poor reattachment
Physics and Model Behavior: Passage Rotation

• Impact of rotation on a duct flow often termed “Coriolis Effect”
  • As flow moves radially outward:
    – Flow tangential velocity is less than that of walls
    – Core flow collects against trailing wall
  • As flow moves radially inward:
    – Flow tangential velocity is greater than that of the walls
    – Core flow collects against leading wall
• Counter Rotating vortices develop
  – Secondary flow structure perpendicular to that induced by turning at bends

Effects of rotation in a straight square passage, Courtesy HOST documentation
**Physics and Model Behavior**

**Rotation + Turning**

- Through the turn, the Coriolis force and the Dean vortex generation counteract each other.
- The result is complex turbulent flows influenced by
  - Centrifugal instability
  - Apparent Coriolis forces
  - Separation / Reattachment
- An unfortunate limitation of standard LEVM is a single turbulent length scale, where smaller scale eddies are immediately dissipated by the model.
- The SAS model can avoid the damping by inclusion of a source term to adjust the length scale locally
  - Where the “resolved length scale” approach the von Karman length scale, the model is allowed to operate in “LES-like” mode by limiting the eddy viscosity.
HOST: Geometry and Nomenclature

- HOST experiment
  - 4 leg square passage
  - Heated wall sections maintained at constant temperature (±2°F)
    - Heated plates labeled by letter (A through R)
    - Heat flux measured and heat transfer coefficient calculated based on local bulk temperature
      - Local \( t_{bulk} \) based on energy balance
    - HTC then converted to a normalized Nusselt (\( Nu/Nu_{\infty} \)) based on fully developed duct flow correlation
      - \( Nu_{\infty} = 0.0176 \times (Re)^{0.8} \)
  - Inner bend walls and final leg not heated
  - Chamfers
    - 1mm chamfers reported at corners of serpentine passage
    - Passage dimension, 0.5” by 0.5”
      - \( D_h = 0.5176” \)
      - Chamfers reduce cross sectional area slightly
**HOST: Geometry and Nomenclature**

- 3-D model with skewed turbulators shown
- Inner bend walls and fourth leg unheated
- Turbulators
  - Smooth / rounded
  - Staggered
  - Blockage Ratio: 10%
  - Pitch Ratio: 10
  - Straight (flow-normal) and 45° skewed turbulators considered
- Distance from axis of rotation to 1st heated section: 49 \( D_h \)

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Smooth  
Straight  
Turbulator Geometry  
Inlet  
Outlet  
Trailing Endwall  
Leading Endwall  
Side Outer  
Unheated Wall  
Rotation Axis
Texas A&M Experimental Data

• Similar to HOST program data, with the following differences:
  – Geometry more clearly defined
    • Bend dimensions explicitly provided
    • Aspect ratio 2:1
    • 2 pass circuit
    • Non-staggered 45 degree turbulators

  – Higher resolution of experimental data

• Inlet condition
  – Flow enters through hole in passage side and turns to flow along passage

  – Velocity and turbulence information at CFD domain inlet unavailable

ASME Journal of Turbomachinery Vol. 124, APRIL 2002

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Reynolds #</td>
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<tr>
<td>Density Ratio $\Delta \rho / \rho$</td>
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<tr>
<td>Rib height to hydraulic diameter (e/D_h)</td>
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<tr>
<td>Rib pitch-to-height (P/e)</td>
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</tr>
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</table>
**University of Manchester Experimental Data**

- 2 Pass Circuit rotated on turntable
  - Axis of rotation near center of test article (not explicitly documented)
  - Presents unfortunate uncertainty in comparison to CFD
- Experimental heat transfer contour plots in rotating passage
  - Liquid crystal approach used to generate contours from experiment
  - Allows for qualitative comparison to CFD

- Working fluid is water

- URANS SST applied
  - Pseudo-time averaging not possible for 2-D heat transfer data
  - Time averaged Nusselt # ratio
  - Normalized by Dittus Boelter

---

<table>
<thead>
<tr>
<th>Reynolds Number</th>
<th>Inflowing leg velocity (m/s)</th>
<th>Prandtl Number</th>
<th>$T$ in ($^\circ$C)</th>
<th>$\Omega$ (rad/s)</th>
<th>Rotation Number</th>
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</table>

CFD Model Selection

• CFD model settings and inputs investigated

  – Baseline HOST geometry and operating point used for model calibration
  – Sensitivity to Mesh resolution, Boundary Conditions, and Turbulence modelling evaluated

  – Resultant model setup used in model validation across different operating points and geometries
**Grid Independence Study**

- Structured and unstructured meshes of varying resolution generated to evaluate grid dependence of solution

- Rotating baseline conditions with normal turbulators considered

- RKE used for grid independence study
  - Performed prior to final turbulence model selection

- Consistent result between all hex meshes
  - Disagreement with tet results
    - Increased tet refinement improves agreement
  - Plate G strongly affected
# Grid Independence Study

- Mesh type and resolution varied
  - Impact of mesh changes evaluated
    - Low mesh sensitivity reduces risk of discretization error as factor in future analysis
  - RKE turbulence model used
    - Consistently solid convergence
- Result
  - Hex meshes for validation target 30 M elements
  - Tet mesh in upcoming analysis should be dense to account for uncertainty

<table>
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<tr>
<th>Type</th>
<th>Element Count</th>
<th>Node Count</th>
<th>Average plate error (from nominal)</th>
<th>Temperature Out (F)</th>
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<td>5.9 M</td>
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<tr>
<td>Hex</td>
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<td><strong>33.1 M</strong></td>
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<td>5.10 %</td>
<td>603.8</td>
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</table>

* 32 M element Hex mesh considered nominal
Final Mesh Details

- 30 M element count targeted based on grid independence study

- Smooth element distribution along and away from walls

- Stretching ratio maintained below 1.2

- Block topology generated to accommodate 45 degree skew of turbulators
  - Half turbulators closed out smoothly
**Mesh Summary**

- Hex meshes to be used for HOST validation suite
- Mesh generated and smoothed in Gridpro
- All upcoming HOST results calculated on mesh as shown

<table>
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<th>Geometry</th>
<th>Element Count</th>
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<tr>
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<tr>
<td>Normal Turbulators</td>
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<tr>
<td>Skewed Turbulators</td>
<td>31 M</td>
<td><img src="image" alt="Skewed Turbulators Mesh" /></td>
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</table>
Turbulence model comparison

• Turbulence model comparison at baseline conditions
  – Stationary and rotating
  – Smooth walled HOST geometry

• RKE, SST, RSM, and SAS evaluated
  – RSM Omega scheme selected
    • Recommended by fluent for situations with high curvature
Turbulence model comparison:
Rotating, Smooth

![Graphs showing Nu/Nu_inf ratio for different stations and models.](image)

- **Experiment**
- **RKE**
- **SST**
- **RSM**
- **SAS**

**Legend:**
- **Leading**
- **Trailing**
- **Inner**
- **Outer**

**Station:**
- A
- B
- C
- D
- E
- F
- G
- H
- I
- J
- K
- L
- M
- N
- P
- R

**Date:** 4/27/2015

**Author:** Daniel Wilde
Turbulence Model Study: Conclusions

- Omega based models exhibit greater local variations from experiment, but achieve better overall data match.

- Baseline operation for skewed turbulator geometry, rotating and stationary.

<table>
<thead>
<tr>
<th>Model</th>
<th>Net % error</th>
<th>RMS % error</th>
<th>Net % error</th>
<th>RMS % error</th>
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Summary of data match with various turbulence models.

45 degree plot of Suction Side heat transfer with various turbulence models.
Validation Approach

- Validation to various experimental data sets:
  - NASA HOST experimentation program
    » 4 pass, square duct with variation in parameters:
      • Rotation number
      • Reynolds Number
      • Density Ratio
      • Rotation Angle
      • Turbulator Configuration
  - Texas A&M data
    » 2 pass rotating turbulated passage with higher resolution data sampling
  - University of Manchester Data
    » 2 pass smooth passage with 2-D experimental Nusselt number contours
- CFD performed at selected experimental points for each experimental program to provide robust understanding of model behavior
## HOST Data CFD Validation Suite

<table>
<thead>
<tr>
<th>Case</th>
<th>Re Number</th>
<th>Ro Number</th>
<th>Inlet Density Ratio</th>
<th>Turbulators</th>
<th>Description</th>
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<tr>
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<td>Effect of Density Ratio</td>
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<tr>
<td>5</td>
<td>25,000</td>
<td>0.24</td>
<td>0.13</td>
<td>Straight</td>
<td>Effect of Reynolds Number</td>
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<td>0.13</td>
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<td>0.13</td>
<td>45 deg</td>
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<td>0.13</td>
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</table>
Illustration of flow Behavior: Smooth Stationary Baseline Case

- Dean Vortices apparent
- Relatively calm behavior otherwise
Illustration of flow Behavior:
Skewed, Stationary Baseline Case

- Turbulators add secondary flow component to flow
- Interaction with Dean Vortices is complex

Looking toward Leading (Suction Side) Wall

Volume Rendering of Velocity
3-D Streamlines colored by Velocity
Illustration of flow Behavior: Skewed, Stationary Baseline Case

- Rotation further complicates flow
- Coriolis effectively pulls flow away from leading wall of outflowing sections

Volume Rendering of Velocity

3-D Streamlines colored by Velocity

Looking toward Leading (Suction Side) Wall
HOST Validation: Passage Heat Transfer

- Net heat transfer summary:
  - Indicates accuracy of heat transfer prediction and sensitivity to changes in operating point
- HOST program error analysis indicates up to 30% error by end of passage due to temperature calculation
  - Up to 6% error in first passage
  - True for all experimental results shown

<table>
<thead>
<tr>
<th></th>
<th>Qt,exp</th>
<th>Qt,cfd</th>
<th>Diff</th>
<th>% change from baseline (experiment to experiment)</th>
<th>% change from baseline (CFD to CFD)</th>
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<td>St. smooth</td>
<td>468.12</td>
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<td>2.91%</td>
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<td>_</td>
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<tr>
<td>St. skewed</td>
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<td>624.52</td>
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<td>107.51%</td>
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</tbody>
</table>

* % change from baseline illustrates sensitivity to changes in operating condition
HOST Validation: Baseline operation

- Total heating backed out from experiment
  - Large scale heat transfer modelled well within experimental error
    - All 4 sides together
    - Scalar results for total heat flux through passage
  - Sudden jumps in bends due to plate distribution
    - Model predicted heat transfer well except local variations and inlet effect

<table>
<thead>
<tr>
<th></th>
<th>Qt.exp</th>
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</tr>
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<td>Skewed turb.</td>
<td>606.22</td>
<td>609.95</td>
<td>0.62%</td>
</tr>
</tbody>
</table>

Total Btu/hr through heated plates
Conclusions

• Modelling effort undertaken to:
  – Explore model sensitivity to assumptions and inputs
  – Ability of selected CFD model to capture impact of changes to passage operating point
Questions?

Thank You