Improving Durability of Turbine Components Through Trenched Film Cooling and Contoured Endwalls

DOE Award Number DE-FE0005540
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Background image: [Hamed, A., Tabakoff, W., and Wenglarz, R., 2006]
**PSU Completed Milestones:**

**DOE Award DE-FE0005540, UTSR Project 07-01-SR127**

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<th>Contoured</th>
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<td>Measure Contoured Endwall Overall Effectiveness with TBC</td>
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<td>Computational Predictions of Conjugate Heat Transfer, with and without TBC</td>
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<td>Measure Overall Effectiveness with Optimized Endwall Design (Contoured)</td>
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**Supplementary Tasks (not in original proposal):**

- Flat Endwall
- Contoured
Better understanding of endwall cooling and its interaction with endwall contouring is needed to predict performance.

Heat Transfer Coefficients

Adiabatic Wall Temperature

\[ \eta = \frac{T_{\infty} - T_{aw}}{T_{\infty} - T_{c,exit}} \]

Praisner et al. [2007] – Pack-B contour

Lynch et al. [2011]
Conjugate heat transfer measurements and predictions of flat and contoured endwalls will be presented.

Flat Endwall
Overall Effectiveness

Contoured Endwall Effectiveness and Flow Measurements

Overall Effectiveness with Deposition

Endwall Effectiveness with TBC
Matching the geometry, Biot number and $h_\infty/h_i$ to engine conditions allows direct measurement of metal temperature.

Overall effectiveness (metal temperature)

$$\phi = \frac{T_\infty - T_w}{T_\infty - T_{c, in}} = 1 - \frac{1 - \eta}{1 + B\infty + h_\infty/h_i} + \eta$$

$$\eta = f(\text{Re}, M, \text{geometry})$$

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<th>Typical Engine</th>
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<tr>
<td>$\text{Re}_\infty,\text{in} \ (Cax)$</td>
<td>$1.25 \times 10^5$</td>
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</tr>
<tr>
<td>$h_\infty/h_i$</td>
<td>1</td>
<td>0.5 - 2.3</td>
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<tr>
<td>$M = (\rho_c U_c/\rho_\infty U_\infty)$</td>
<td>1 - 2</td>
<td>0.6, 1, 2</td>
</tr>
<tr>
<td>$B\infty = h_\infty t/k_w$</td>
<td>0.27</td>
<td>0.30 - 0.77</td>
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Mainstream flow is heated, and coolant flow is chilled to maximize driving $\Delta T = T_\infty - T_{c,\text{internal}}$.
Thermocouples were installed on the endwall surface under the TBC to measure $\phi_{TBC}$ along two streamlines.
The measurements of overall effectiveness demonstrated the key features of film cooling and internal impingement.

Film Cooling Only, \( \phi_f \)

Impingement Cooling Only, \( \phi_o \)

Combined Film and Impingement, \( \phi \)

in-hole convection

uniform high effectiveness

\[ M_{avg} = 2.0 \]

\[ \phi = \frac{T_\infty - T_w}{T_\infty - T_{c,in}} \]
Increasing blowing ratio improved average $\phi$ for impingement more than for film cooling.
Conjugate RANS simulations used the SST $k$-$\omega$ model and an unstructured computational grid with wall prism layers.

**FLUENT – SIMPLE**

RANS, SST $k$-$\omega$, & energy – 2nd order

Flow grid – 9.8 M cells

Flow and solid domains thermally coupled

- Velocity inlet
- Periodic boundaries
- Adiabatic

- Blade
- Outflow
- Conducting endwall

- Plenum
- TBC grid, 0.3 M cells
- Endwall grid, 1.5 M cells
- Impingement plate
There is good overall agreement between the measured and predicted $\phi$, except for the attachment of the jets.
CFD temperature results show the three-dimensional conduction and steep gradients within the endwall.

- Viewing direction

\[ x/C_{ax} = 0 \]

**1\textsuperscript{st} row of impingement holes**

- **Mainstream**
- **Endwall**
- **Imp. Plate**
- **Plenum**

\[ M_{avg} = 1.0 \]

\[ M_{avg} = 2.0 \]

\[ \frac{T_\infty - T}{T_\infty - T_{c,in}} \]
We simulated deposition with wax, matching the Stokes number, Thermal Scaling Parameter and conductivity ratio.

\[
\text{Stk} = \frac{\text{particle relaxation time}}{\text{fluid time scale}} = \frac{\rho_p d_p^2 U_p}{18 \mu L_c} = 6.54
\]

TSP = \( \frac{t_1 + t_2}{L_\infty / U_{\infty,i}} \) = 0.3

- TSP < 1 Solid
- TSP > 1 Molten

\[
\frac{k_{\text{deposit}}}{k_{\text{wall}}} = 0.069 \quad \frac{k_{\text{wax}}}{k_{\text{Corian}}} = 0.11
\]

\[
T_{\text{initial}} = 1320 \quad T_{\text{gas}} = 1220 \quad T_{\text{solid}} = 1260^\circ C
\]

Particle Phase

Fly Ash Particle Temperature (C)

1300
1280
1260
1240
1220
10 \mu m Fly Ash

\[
L_c / U_{\infty,i}
\]
The cooling systems mitigated some deposition, but effectiveness was reduced everywhere in the passage.

\[
\phi = \frac{T_\infty - T_w}{T_\infty - T_{c,in}} \quad \text{or} \quad \omega = \frac{T_\infty - T_{\text{wax}}}{T_\infty - T_{c,in}}
\]

\[M_{\text{avg}} = 1.0\]
We observed clear areas due to the film cooling jets, and deposition on the blade from the passage vortex.

\[ \phi_f = \frac{T_\infty - T_{w,f}}{T_\infty - T_{c,\text{int}}} \]

\[ \omega_f = \frac{T_\infty - T_{wax,f}}{T_\infty - T_{c,\text{int}}} \]

\[ M_{\text{avg}} = 1.0 \]

Evidence of passage vortex.
Roughness from the deposition degrades the cooling performance, resulting in higher endwall temperatures.

\[
\phi_i, \ M_{\text{avg}} = 0.6 \\
\phi_{i,\text{dep}}, \ M_{\text{avg}} = 0.6 \text{ w/ deposition} \\
\phi_i, \ M_{\text{avg}} = 1.0 \\
\phi_{i,\text{dep}}, \ M_{\text{avg}} = 1.0 \text{ w/ deposition}
\]

Film Only
Film & Impingement

\[h_\infty \text{ increased by 30-100\% w/ deposition}\]
Although the Nu peaks at H/D = 2.9, the area averaged $\phi$, with film and impingement, is relatively insensitive to H/D.
Contouring reduces effectiveness for impingement only, since $h_i$ decreases and $h_\infty$ increases from the flat endwall.
Overall effectiveness does not change much between the flat and contoured endwall with film cooling.

Film and Impingement Cooling

- Flat, $M_{avg} = 0.6$
- Flat, $M_{avg} = 1.0$
- Flat, $M_{avg} = 2.0$
- Contoured, $M_{avg} = 0.6$
- Contoured, $M_{avg} = 1.0$
- Contoured, $M_{avg} = 2.0$
Although the average overall effectiveness is the same for the flat and contoured endwall, there are local differences.
Other than film attachment, the contoured endwall simulations predict the same trends as the measurements.

$M_{avg} = 1.0$

$M_{avg} = 2.0$

$\phi = \frac{T_\infty - T_w}{T_\infty - T_{c,in}}$
The trailing edge flowfield was measured using a time resolved particle image velocimetry (PIV) system. Flowfield was sampled for 3000 or 6000 images at $\Delta t = \delta/U_\infty$. Cross correlation was performed using LaVision software, and the interrogation window was $0.035D \approx 4\delta$. High speed cameras were used to capture the flowfield images.
The trailing edge flowfield was measured for three vertical planes to capture the passage vortex development.
The passage vortex, indicated by the low velocity region, moves farther away from the wall with film cooling.

- $M_{avg} = 2.0$
- $z = 0$
- $z = 0.32S$

No Film Cooling

Plane A

Plane B

Plane C
Contours of turbulent kinetic energy show two bands of peak $tke$, indicating the presence of two vorticies.

$\frac{TKE}{U_{\infty}^2}$

- Plane C
- Plane B
- Plane A

$z = 0$ Endwall
$z = 0.32S$ Endwall
$z = 0.32S$ Trailing Edge
$M_{avg} = 2.0$
To accurately quantify the thermal effect of TBC, the thermal resistance was scaled to match the engine.

Overall effectiveness with TBC
\[
\phi_{\text{TBC}} = \frac{T_\infty - T_w}{T_\infty - T_{c,\text{in}}} = \frac{1 - \chi \eta}{1 + \frac{\text{Bi}_\infty + h_\infty/h_i}{\text{Bi}_\infty (R_{\text{TBC}}/R_w) + 1}} + \chi \eta
\]

TBC effectiveness
\[
\tau = \frac{T_\infty - T_{\text{TBC}}}{T_\infty - T_{c,\text{in}}}
\]

\[
\chi \eta = f(\text{Re}_\infty, M, \text{geometry})
\]

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<td>( \frac{R_{\text{TBC}}}{R_w} = \frac{t_{\text{TBC}} k_w}{t_w k_{\text{TBC}}} )</td>
<td>0.6–9.3</td>
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The conjugate simulations predict significant and uniform cooling with TBC for the flat endwall. When $M_{avg} = 1.0$, without TBC, $\phi_{flat} = 0.19$ and with TBC, $\phi_{TBC} = 0.32$. When $M_{avg} = 2.0$, without TBC, $\phi_{flat} = 0.22$ and with TBC, $\phi_{TBC} = 0.39$. The temperature $T_w$ is calculated as $T_w = \frac{T_\infty - T_{c,in}}{T_\infty - T_{c,in}}$. The legend on the right side of the diagram shows the color scale for temperature variation.
The conjugate simulations predict similar improvements with TBC for the contoured endwall with small differences

No TBC - Predicted $T_w$

With TBC - Predicted $T_w$

$M_{avg} = 1.0$

$\bar{\phi_{flat}} = 0.19$

$M_{avg} = 2.0$

$\bar{\phi_{flat}} = 0.22$

$\phi_{TBC} = \frac{T_\infty - T_w}{T_\infty - T_{c,in}}$

$\phi_{flat} = 0.33$

$\phi_{flat} = 0.38$
Endwall contouring measurements along the streamlines are similar to the flat endwall, with and without TBC.

\[
\begin{align*}
&\phi \text{ Flat} \\
&\phi_{TBC} \text{ Flat} \\
&\phi \text{ Contoured} \\
&\phi_{TBC} \text{ Contoured}
\end{align*}
\]

SS, \(M_{\text{avg}} = 0.6\)

SS, \(M_{\text{avg}} = 1.0\)

SS, \(M_{\text{avg}} = 2.0\)
Adding TBC improves $\phi$ more than an increase in blowing ratio because TBC reduces heat transfer

\[
\Delta \phi_M \approx 0.05
\]

\[
\Delta \phi_{TBC} = \phi_{TBC} - \phi \approx 0.15
\]

Net Heat Flux Reduction
- outer endwall surface

\[
\Delta q_r = \frac{q_w - q_{w,TBC}}{q_w}
\]

$\Delta \phi_{TBC}$ also increases with $M$

- Measured $\phi_{flat}$ improvement w/ TBC
- Predicted $\phi_{flat}$ improvement w/ TBC
- Predicted flat $\Delta q_r$ w/ TBC
- Measured $\phi_{cont}$ improvement w/ TBC
- Predicted $\phi_{cont}$ improvement w/ TBC
- Measured contoured $\Delta q_r$ w/ TBC

\[
\Delta \phi_{TBC}
\]

\[
\Delta q_r
\]
TBC temperature is less affected by the internal cooling and more affected by the film cooling performance.
This study demonstrates conjugate heat transfer trends for gas turbine endwalls and the secondary flow effects.

Good agreement between conjugate measurements and CFD predictions.

- Measured $\phi$
- Predicted $\phi$

Demonstrate trends for:

- Contouring
- Cork - TBC
- Deposition

Unique flowfield measurements demonstrate interactions between passage vortex and film cooling.

- Turbulent Kinetic Energy with film cooling
- Temperature gradients with TBC