Temperature Mapping of Air Film-Cooled Thermal Barrier Coated Surfaces Using Cr-Doped GdAlO$_3$ Phosphor Thermography

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Motivation for Evaluating Combined TBC + Air-Film Cooling

• TBC and air film cooling effectiveness usually studied separately.
• TBC and air film cooling contributions to cooling effectiveness are interdependent and are not simply additive.
• Combined cooling effectiveness must be measured to achieve optimum balance between TBC thermal protection and air film cooling.
Heat Transfer Through TBC

TBC-centric view

Mainstream Hot Gas Flow

$T_{\text{mainstream}}$

$q = h_{\text{conv}}(T_{\text{mainstream}} - T_{\text{surface}})$

Heat flux across TBC:

$q = -k_{TBC} \frac{dT}{dx} = \frac{k_{TBC}}{d_{TBC}} |\Delta T_{TBC}|$

Fixed $q$ drives heat transport.

Thermal protection:

$T_{\text{mainstream}} - T_{\text{metal}} = q\left[\frac{1}{h_{\text{conv}}} + \frac{d_{TBC}}{k_{TBC}}\right]$

For $d_{TBC}/k_{TBC} \gg 1/h_{\text{conv}}$, thermal protection linearly increases with $d_{TBC}/k_{TBC}$.
Heat Transfer Through Turbine Blade/Vane
overall heat transfer view

Mainstream Gas Flow

**T_{mainstream}**

Overall heat transfer view

**T_{coolant gas}**

**T_{air film}**

**\Delta T_{surface convection}**

**\Delta T_{TBC}**

**\Delta T_{metal}**

**\Delta T_{backside convection}**

Total heat flux:  
\[ q = U \left[ T_{mainstream} - T_{coolant} \right] = U \Delta T_{total} \]

Overall heat transfer coefficient:  
\[ \frac{1}{U} = \frac{1}{h_{conv}} + \frac{d_{TBC}}{k_{TBC}} + \frac{d_{metal}}{k_{metal}} + \frac{1}{h_{backside}} \]

Cooling effectiveness:  
\[ \Phi = \frac{T_{mainstream} - T_{metal}}{\Delta T_{total}} = \frac{1}{h_{conv} k_{TBC}} + \frac{d_{TBC}}{k_{TBC}} + \frac{d_{metal}}{k_{metal}} + \frac{1}{h_{backside}} \]

Increasing \( d_{TBC} \) & decreasing \( k_{TBC} \) will have diminishing returns, especially with air film cooling.
TBC & Air-Film Contributions to Cooling Effectiveness

**TBC contribution:**

\[ \Phi_{TBC} = \frac{\frac{d_{TBC}}{k_{TBC}}}{\frac{1}{h_{conv}^{eff}} + \frac{d_{TBC}}{k_{TBC}} + \frac{d_{metal}}{k_{metal}} + \frac{1}{h_{backside}}} \]

- Air film cooling greatly reduces effective \( h_{conv} \) and therefore greatly reduces \( \Phi_{TBC} \)
- Air film cooling greatly reduces \( q \) and therefore \( \Delta T_{TBC} \)
- TBC does not carry significant penalty for engine efficiency.

**Air film cooling contribution:**

\[ \Phi_{airfilm} = \frac{\frac{1}{h_{conv}^{eff}}}{\frac{1}{h_{conv}^{eff}} + \frac{d_{TBC}}{k_{TBC}} + \frac{d_{metal}}{k_{metal}} + \frac{1}{h_{backside}}} \]

- TBC reduces \( \Phi_{airfilm} \)
- Putting insulator between air film and metal decreases effectiveness of air film cooling.
- Air film cooling carries significant penalty for engine efficiency.

- \( \Phi_{overall} > \Phi_{TBC}, \Phi_{airfilm} \) (TBC, air film cooling always beneficial)
  - But returns can be diminishing.
- TBC is better for reducing air film cooling requirements (increasing engine efficiency) than increasing temperature capability of air film cooled component.
- Experimental measurements of combined TBC + air film cooling effectiveness are needed to evaluate TBC/air-film-cooling tradeoffs.
Objectives

• Experimentally map (2D) cooling effectiveness of air film cooling of TBC-coated surfaces.
  – Cooling effectiveness at the TBC surface (to be presented today)
  – Cooling effectiveness at the metal surface (future)
• Examine changes in cooling effectiveness as a function of:
  – Mainstream hot gas temperature
  – Blowing ratio (cooling air flow)
• Examine interplay between air film cooling, backside impingement cooling, and through-hole convective cooling for TBC-coated substrate.
Approach

• Perform measurements in NASA GRC Mach 0.3 burner rig.
  – Vary flame temperature and blowing ratio.
• Perform measurements on TBC-coated superalloy plate.
  – 200 µm EB-PVD YSZ on Hastelloy X plate with MCrAlY bond coat
• Use scaled-up cooling hole geometry.
• Perform 2D temperature mapping using Cr-doped GdAlO$_3$ (Cr:GAP) phosphor thermometry.
  – GdAlO$_3$ exhibits orthorhombic perovskite crystal structure: gadolinium aluminum perovskite (GAP).
  – Ultrabright Cr:GAP luminescence emission enable surface temperature mapping using luminescence lifetime imaging by simply broadening the excitation laser beam to cover the region of interest.
  – Unbiased by emissivity changes and reflected radiation. ✓
  – Can be utilized for subsurface temperature mapping (future). ✓
  – Only applicable to steady state temperatures. ❌
• Convert temperature maps into cooling effectiveness maps.
Cooling Hole Plate Geometry

**Side view**
- 6.35 mm
- 30°

**Top view**
- 76.4 mm
- 50.8 mm
- 3.175 mm
- 9.525 mm

**Coating layers**
- 6.35 mm
- 125 μm
- 200 μm
- 30 μm

**Materials**
- Cr:GAP
- YSZ
- MCrAlY
- Hastelloy X

**Coating method**
- EB-PVD
Cooling Effectiveness Measurements

Conventional Air Film Cooling Effectiveness Test
- Uniform mainstream flow (velocity & temperature)
- Typical surface temperatures: < 100°C
- Pure air film cooling
  - No heat flux (insulating substrate)
  - No backside impingement cooling
- Measure adiabatic air film cooling effectiveness, $\eta$
  $$\eta = \frac{T_{\text{mainstream}} - T_{\text{adiabatic}}}{T_{\text{mainstream}} - T_{\text{coolant exit}}}$$
- $\eta$ is a fundamental characterization of air film cooling effectiveness
- Measure $\eta$ as a function of blowing ratio, $M$
  $$M = \frac{\rho_{\text{coolant}} V_{\text{coolant}}}{\rho_{\text{mainstream}} V_{\text{mainstream}}}$$

Burner Rig Air Film Cooling Effectiveness Test
- Divergent mainstream flow
- Typical temperatures: 600-1100°C
- Air film + backside impingement + thru-hole convection
- Measure overall surface cooling effectiveness, $\eta'$
  $$\eta' = \frac{T_{\text{uncooled}} - T_{\text{cooled}}}{T_{\text{uncooled}} - T_{\text{coolant enter}}}$$
- $\eta'$ is a nonfundamental but realistic characterization of combined surface cooling effects
- Measure $\eta$ as a function of $M'$
  $$M' = \frac{\rho_{\text{coolant}} V_{\text{coolant}}}{\rho_{\text{mainstream}} V_{\text{mainstream}}^{\text{max}}}$$
Demonstrating Temperature Measurement Capability
Time-Averaged Luminescence Emission from Cr(0.2%):GAP Puck
Temperature Dependence

532 nm excitation
Luminescence Decay Curves Obtained by Time-Gated Imaging

Intensity (counts) vs. Time (µsec)

- 100°C
- 1000°C
- 10000°C
- 100000°C

Temperatures:
- 183°C
- 733°C
- 783°C
- 807°C
- 831°C
- 855°C
- 879°C
- 904°C
- 931°C
- 953°C
- 977°C
- 1002°C
- 1027°C
- 1052°C
- 1076°C
- 1100°C
- 1127°C
2D Temperature Mapping by Luminescence Lifetime Imaging

- Image stack collection
- Background subtraction
- Data filtering
- Pixel by pixel lifetime analysis
  - Fitting window selection
  - Fit to exponential decay
  - Removing flame burst outliers
  - Use calibration curve to convert decay time to temperature
  - Convert temperature to cooling effectiveness
Luminescence Lifetime Image Stack

$n$ images
$t_0 = \text{start of 1}^{\text{st}} \text{ exposure}$
$\Delta t = \text{frame interval}$
$t_n = (n-1)\Delta t + t_0$
$= \text{delay time after laser pulse for}$
$n^{\text{th}} \text{ image in stack}$

Typical values
$n = 64$
$t_0 = 0.1 \ \mu\text{s}$
$\Delta t = 0.25 \text{ to } 100 \ \mu\text{s}$
Frame interval = exposure = $\Delta t$
Laser pulse frequency = 20 Hz
1 exposure/laser pulse (ICCD)
2D Temperature Maps from Luminescence Lifetime Imaging

- **Multi-step procedure:**
  - Step 1: Remove thermal radiation background from each image collected.
  - Step 2: Collect sequence of background-corrected time-gated images over sequence of delay times.
2D Temperature Maps from Luminescence Lifetime Imaging

– Step 3: Fit luminescence decay curve at each pixel to produce decay time map (Matlab routine).

Individual Pixel Decays

- \( \tau = 256 \, \mu s \) (726°C)
- \( \tau = 69 \, \mu s \) (827°C)

Decay Time Map

- 95% Confidence Interval

– Step 4: Use calibration data to convert decay time map to temperature map (Matlab routine).

Find \( T \) that gives know \( \tau \) where

\[
\tau = \tau^E \left\{ \frac{1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta E + \Delta E)/kT}} \right\}
\]

Temperature Map

Temperature Line Scan

95% Confidence Interval

1 cm
Background Radiation Sources

- Thermal (blackbody) radiation emitted by plate
- Reflected thermal and chemiluminescence radiation emitted from combustor.
- Luminous flame particles moving through field of view
Background Radiation Sources
Surface Thermal & Reflected Combustor Radiation

30% air, 17% fuel

30% air, 8.5% fuel

23% air, 27% fuel

20°C blackbody
Pre-Fit Data Filtering
Pre-Fit Data Filtering
Pixel Removal Criteria

Minimum static threshold
\[ I_{ij}(\text{frame 1}) < 3200 \]

Minimum dynamic threshold
\[ I_{ij}(\text{last frame}) > 10\% * I_{ij}(\text{first frame}) \]

Minimum number of frames in fitting interval
\[ 10\% * I_{ij}(\text{first frame}) < I_{ij}(\text{frame } n) < 90\% * I_{ij}(\text{first frame}) \]

Number of frames < 10

Insufficient signal
 Too cold to capture sufficient percentage of decay
 Too hot to capture sufficient number of frames in fitting window

Post-fit temperature map

Number of frames in fitting window
Fitting Window Selection
Effect of Fitting Window Selection

60% threshold reduces influence of fast initial decay

10% threshold can accept much longer decays to cover greater temperature range

Fit to $I = I_0 e^{-t/\tau}$
Calibration
Calibration of Decay Time vs. Temperature for GAP:Cr Coating
60 to 10% Initial Intensity Fitting Window

Two distinct regions
200°C<T<750°C: less temperature sensitive
T>750°C: more temperature sensitive

Removing Flame Burst Outliers
Effect of Luminous Flame Bursts

Decay time temperature maps
95% confidence interval

includes outlier pixels

excludes outlier pixels

Image Stack

0 μs

1 cm

\[% T_{excluded} - T_{included}\]

1 cm
Effect of Outlier Removal

$I_{ij}(t_n)$ is intensity of pixel $ij$ in frame $n$ of stack,
$t_n = (n-1)\Delta t + t_0$ where $\Delta t$ is frame interval and $t_0$ is 1st frame time;
$I_{ij}(t_n)$ is an outlier when $|I_{ij}(t_n) - I_{ij}^{fit}(t_n)| > 1.5\sigma [I_{ij}(t_n) - I_{ij}^{fit}(t_n)]$

$\tau = 125.1 \mu s \quad (785.9^\circ C)$

$\tau = 92.8 \mu s \quad (807.0^\circ C)$
Air Film Cooling of TBC-Coated Surface

Results

• Examine changes in cooling effectiveness as a function of:
  – Mainstream hot gas temperatures: 1424, 1552, and 1696°C
  – Blowing ratio: $M' = 0$ to $0.9$
Burner Rig 2D Temperature Maps

$T_{\text{mainstream}} = 1424^\circ\text{C}$

Decay time temperature maps

$M' = 0.097$

$M' = 0.291$

$M' = 0.512$

$M' = 0.724$

$M' = 0.789$

\(1\ \text{cm}\)

95% confidence interval

photos
Burner Rig 2D Cooling Effectiveness Maps

$T_{\text{mainstream}} = 1424^\circ\text{C}$

- Initially increasing air film cooling effectiveness
- Slowly increasing backside impingement cooling effectiveness
- Vortex-induced hot spot
- Rapidly increasing through-hole convection cooling effectiveness
- Diminishing air film cooling effectiveness
- Vortex-induced hot streaks outlast air film cooling
Burner Rig 2D Temperature Maps

\[ T_{\text{mainstream}} = 1552^\circ C \]

Decay time temperature maps

\[ M' = 0.101 \quad M' = 0.302 \quad M' = 0.503 \quad M' = 0.755 \quad M' = 0.880 \]

\( \backslash 1 \text{ cm} \)

95% confidence interval

photos
Burner Rig 2D Cooling Effectiveness Maps

$T_{\text{mainstream}} = 1552^\circ$C

- $M' = 0.201$
- $M' = 0.302$
- $M' = 0.402$
- $M' = 0.503$
- $M' = 0.629$
- $M' = 0.755$
- $M' = 0.880$

Initially increasing air film cooling effectiveness

Slowly increasing backside impingement cooling effectiveness

Increasing through-hole convection cooling effectiveness

Slowly decreasing air film cooling effectiveness

Weaker vortex-induced hot spot
Burner Rig 2D Temperature Maps

$T_{\text{mainstream}} = 1696^\circ C$

Compromised by surface fouling and plenum leak

Decay time temperature maps

<table>
<thead>
<tr>
<th>$M'$</th>
<th>Temperature Map</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td><img src="image1" alt="Image" /></td>
</tr>
<tr>
<td>0.209</td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>0.314</td>
<td><img src="image3" alt="Image" /></td>
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<td>0.654</td>
<td><img src="image4" alt="Image" /></td>
</tr>
<tr>
<td>0.785</td>
<td><img src="image5" alt="Image" /></td>
</tr>
</tbody>
</table>

$\backslash 1\text{ cm}$

95% confidence interval

<table>
<thead>
<tr>
<th>$M'$</th>
<th>Confidence Interval Map</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>0.209</td>
<td><img src="image7" alt="Image" /></td>
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<tr>
<td>0.314</td>
<td><img src="image8" alt="Image" /></td>
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<tr>
<td>0.654</td>
<td><img src="image9" alt="Image" /></td>
</tr>
<tr>
<td>0.785</td>
<td><img src="image10" alt="Image" /></td>
</tr>
</tbody>
</table>

photos
**Effect of Surface Deposition/Fouling**

\[ T_{\text{mainstream}} = 1424^\circ \text{C} \]

**Pre-fouling**

- \[ M' = 0.512 \]

![Decay time temperature maps](image)

**Post-fouling**

- \[ M' = 0.483 \]

![95% confidence interval](image)

- **M' = 0**

- **Fouling changes emissivity**

- **Deposition/fouling does not bias temperature measurement but does reduce measurement precision.**
Combined Cooling Effects Summary

- **Air film cooling**
  - Effectiveness initially increases with increasing M, then diminishes with jet lift-off.
  - Effectiveness retained better at high flame temperature.
  - Vortex-induced hot streaks appear near cooling holes. Hot streaks remain prominent even when air film cooling is lost. May be worse on TBC-coated surface.

- **Through-hole convective cooling**
  - Effectiveness increases rapidly at high M.
  - Not observed in conventional air film cooling measurements.

- **Backside impingement cooling**
  - Slowly increases with increasing M.

- **Effect of TBC**
  - Will decrease air film cooling effectiveness.
  - Will increase through hole convective cooling effectiveness – may be useful for showerhead cooling.
Future Direction
Add Metal Temperature Maps

Mainstream Gas Flow

$T_{\text{mainstream}}$ $T_{\text{air film}}$

Surface cooling effectiveness from Cr:GAP layer:

$$\eta' = \frac{T_{\text{surface cooled}} - T_{\text{surface uncooled}}}{T_{\text{coolant enter}} - T_{\text{coolant enter}}}$$

Metal cooling effectiveness from doped YSZ layer:

$$\phi' = \frac{T_{\text{metal cooled}} - T_{\text{metal uncooled}}}{T_{\text{coolant enter}} - T_{\text{coolant enter}}}$$
Conclusions

• Successfully demonstrated 2D temperature mapping by Cr:GAP phosphor thermometry with high resolution (temperature, spatial, but not temporal) in presence of strong background radiation associated with combustor burner flame.
  – Robust, operator independent, automated analysis

• Can be used as new tool for studying/optimizing non-additive interplay of cooling mechanisms for TBC-coated components.
  – TBC
  – Air film
  – Through-hole convection
  – Backside impingement

• TBC affects other cooling mechanisms
  – Degrades air film cooling effectiveness
  – Enhances through-hole convection cooling

• Improved TBCs will reduce air film cooling requirements for higher engine efficiency, but combined TBC + air film cooling will not be effective substitute for CMC + EBC development.