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

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40th International Conference on Advanced Ceramics & Composites
Daytona Beach, FL
January 25, 2016
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

\[ q = h_{conv}(T_{mainstream} - T_{surface}) \]

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:

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

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

Mainstream Gas Flow

$T_{\text{mainstream}}$

$T_{\text{coolant gas}}$

$T_{\text{air film}}$

$\Delta T_{\text{surface convection}}$

$\Delta T_{\text{backside convection}}$

$\Delta T_{\text{TBC}}$

$\Delta T_{\text{metal}}$

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

Overall heat transfer coefficient:

$$\frac{1}{U} = \frac{1}{h_{\text{conv}}} + \frac{d_{\text{TBC}}}{k_{\text{TBC}}} + \frac{d_{\text{metal}}}{k_{\text{metal}}} + \frac{1}{h_{\text{backside}}}$$

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

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

**TBC contribution:**

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

- Air film cooling greatly reduces effective \( h_{\text{conv}} \) 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:**

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

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

- \( \Phi_{\text{overall}} > \Phi_{TBC}, \Phi_{\text{airfilm}} \) (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°
  - 152.4 mm
  - 76.4 mm

- Top view:
  - 9.525 mm
  - 50.8 mm
  - 152.4 mm
  - 3.175 mm
  - 30°

Coating layers:
- Hastelloy X
- MCrAlY
- YSZ
- Cr:GAP

EB-PVD coating process with:
- 6.35 mm
- 125 μm
- 200 μm
- 30 μm
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, \( \eta \)

\[
\eta = \frac{T_{\text{mainstream}} - T_{\text{adiabatic surface}}}{T_{\text{mainstream}} - T_{\text{coolant exit}}}
\]

- \( \eta \) 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

Intensity (arb.units)

Wavelength (nm)

20C
90C
284C
385C
484C
587C
686C
780C
880C
977C

532 nm excitation

bandpass
Luminescence Decay Curves Obtained by Time-Gated Imaging

Intensity (counts) vs. Time (µsec) for various temperatures.
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
$t_0 =$ start of 1st exposure
$\Delta t =$ frame interval
$t_n = (n-1) \Delta t + t_0$

$= \text{delay time after laser pulse for}n$th image in stack

Typical values
$n = 64$
$t_0 = 0.1 \ \mu s$
$\Delta t = 0.25 \ \text{to} 100 \ \mu s$

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

Find $T$ that gives know $\tau$ where

$$\tau = \frac{\tau_2^{R_e} 1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta E + \Delta E)/kT}}$$

Temperature Line Scan

95% Confidence Interval

Individual Pixel Decays

Decay Time Map

95% Confidence Interval
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

Intensity (arb.units)

Wavelength nm

- **30% air, 17% fuel**
- **30% air, 8.5% fuel**
- **1200°C blackbody**

- 23% air, 27% fuel
- 30% air, 8.5% fuel
- 30% air, 17% fuel

- **OH**
- 318nm
- **CH**
- 392nm
- **CH**
- 430nm
- **C2**
- 514nm
- **C2**
- 560nm
- **CO2** + soot broadband
- **specimen thermal radiation broadband**
Pre-Fit Data Filtering
Pre-Fit Data Filtering
Pixel Removal Criteria

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

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

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

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 $I = I_0 e^{-t/\tau}$

$\tau = 43.3 \text{ µs}$

$\tau = 52.8 \text{ µs}$

$\tau = 31.3 \text{ µs}$
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

\ photo

1 cm
$I_{ij}(t_n)$ 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 $|I_{ij}(t_n) - I_{ij}^{fit}(t_n)| > 1.5\sigma [I_{ij}(t_n) - I_{ij}^{fit}(t_n)]$
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

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

Decay time temperature maps

\[ M' = 0.097 \quad M' = 0.291 \quad M' = 0.512 \quad M' = 0.724 \quad M' = 0.789 \]

1 cm

95% confidence interval

photos
Burner Rig 2D Cooling Effectiveness Maps

\( \text{T}_{\text{mainstream}} = 1424^\circ \text{C} \)

- \( M' = 0.291 \) Initially increasing air film cooling effectiveness
- \( M' = 0.369 \) Slowly increasing backside impingement cooling effectiveness
- \( M' = 0.512 \) Vortex-induced hot spot
- \( M' = 0.629 \) Rapidly increasing through-hole convection cooling effectiveness
- \( M' = 0.724 \) Diminishing air film cooling effectiveness
- \( M' = 0.789 \) Vortex-induced hot streaks outlast air film cooling
Burner Rig 2D Temperature Maps

\[ T_{\text{mainstream}} = 1552°C \]

Decay time temperature maps

\[
\begin{array}{ccccc}
M' = 0.101 & M' = 0.302 & M' = 0.503 & M' = 0.755 & M' = 0.880 \\
\end{array}
\]

\[ \sim 1 \text{ cm} \]

95% confidence interval

photos
Burner Rig 2D Cooling Effectiveness Maps

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

- \( M' = 0.201 \):
  - Initially increasing air film cooling effectiveness

- \( M' = 0.302 \):
  - Slowly increasing backside impingement cooling effectiveness

- \( M' = 0.402 \):
  - Increasing through-hole convection cooling effectiveness
  - Slowly decreasing air film cooling effectiveness

- \( M' = 0.503 \):
  - Increasing through-hole convection cooling effectiveness

- \( M' = 0.629 \):
  - Slowly decreasing air film cooling effectiveness

- \( M' = 0.755 \):
  - Weaker vortex-induced hot spot

- \( M' = 0.880 \):
  - Weaker vortex-induced hot spot
Burner Rig 2D Temperature Maps

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

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>
</tr>
<tr>
<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

Photos
Effect of Surface Deposition/Fouling

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

Pre-fouling

M' = 0.512

Decay time temperature maps

95% confidence interval

Post-fouling

M' = 0.483

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.
Mainstream Gas Flow

Future Direction
Add Metal Temperature Maps

Surface cooling effectiveness from Cr:GAP layer:

\[ \eta' = \frac{T_{surface}^{uncooled} - T_{surface}^{cooled}}{T_{uncooled}^{surface} - T_{coolant~enter}} \]

Metal cooling effectiveness from doped YSZ layer:

\[ \Phi' = \frac{T_{metal}^{uncooled} - T_{metal}^{cooled}}{T_{metal}^{uncooled} - T_{coolant~enter}} \]
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.