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

Jeffrey I. Eldridge, Vikram Shyam, Adam C. Wroblewski, and Dongming Zhu
NASA Glenn Research Center, Cleveland, OH

Michael D. Cuy
Vantage Partners, Cleveland, OH

Douglas E. Wolfe
Penn State University, University Park, PA

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:

\[ q = -k_{TBC} \frac{dT}{dx} = \frac{k_{TBC}}{d_{TBC}} \Delta T_{TBC} \]

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**

\[ T_{\text{mainstream}} \]

**Coolant gas**

\[ T_{\text{coolant}} \]

\[ \Delta T_{\text{TBC}} \]

**TBC**

\[ d_{\text{TBC}} \]

**Turbine blade/vane**

\[ d_{\text{metal}} \]

**Metal**

\[ \Delta T_{\text{metal}} \]

\[ \Delta T_{\text{backside convection}} \]

**Air film**

\[ \Delta T_{\text{surface convection}} \]

**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:**

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

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

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

- 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°

Top view:
- 76.4 mm
- 9.525 mm
- 50.8 mm
- 152.4 mm

Coating layers:
- Cr:GAP 30 μm
- YSZ 200 μm
- MCrAlY 125 μm
- Hastelloy X 6.35 mm

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, $\eta$
  \[ \eta = \frac{T_{\text{mainstream}} - T_{\text{adiabatic surface}}}{T_{\text{mainstream}} - T_{\text{cooler exit}}} \]
- $\eta$ 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, $\eta'$
  \[ \eta' = \frac{T_{\text{uncooled}} - T_{\text{cooled}}}{T_{\text{uncooled}} - T_{\text{cooler enter}}} \]
- $\eta'$ 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

![Graph showing temperature vs. luminescence intensity](image-url)

- Intensity (arb.units)
- Wavelength (nm)
- 20°C
- 90°C
- 284°C
- 385°C
- 484°C
- 587°C
- 686°C
- 780°C
- 880°C
- 977°C

532 nm excitation

**Bandpass**
Luminescence Decay Curves Obtained by Time-Gated Imaging

The graph shows luminescence decay curves for various temperatures, ranging from 183°C to 1127°C. The x-axis represents time in microseconds, while the y-axis represents intensity in counts. Each curve corresponds to a different temperature, with distinct colors for clarity.
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
- $t_n = (n-1)\Delta t + t_0$
  - = delay time after laser pulse for $n$th image in stack

Typical values
- $n = 64$
- $t_0 = 0.1$ µs
- $\Delta t = 0.25$ to 100 µs

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

\[ \tau = 256 \, \mu s \quad (726^\circ C) \]

\[ \tau = 69 \, \mu s \quad (827^\circ C) \]

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

\[ T \text{ that gives } \tau \text{ where } \tau = \frac{\tau_0^R}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta Eq+\Delta E)/kT}} \]

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

\[ \tau = \frac{\tau_0^R}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta Eq+\Delta E)/kT}} \]
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

- CH* 392nm
- CH* 430nm
- C2* 475nm
- C2* 514nm
- C2* 560nm
- CO2* + soot broadband

specimen thermal radiation broadband

23% air, 27% fuel
30% air, 8.5% fuel
30% air, 17% fuel
Pre-Fit Data Filtering
Pre-Fit Data Filtering
Pixel Removal Criteria

Minimum static threshold
\( l_{ij}(\text{frame 1}) < 3200 \)

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

Minimum number of frames in fitting interval
\( 10\% \times l_{ij}(\text{first frame}) < l_{ij}(\text{frame } n) < 90\% \times l_{ij}(\text{first frame}) \)
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
200ºC<T<750ºC: less temperature sensitive
T>750ºC: more temperature sensitive

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

Removing Flame Burst Outliers
Effect of Luminous Flame Bursts

Decay time temperature maps vs. 95% confidence interval

- Includes outlier pixels
- Excludes outlier pixels

Image Stack

$T_{excluded} - T_{included}$

Photo

$0 \mu s$

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

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

\[ 1 \text{ cm} \]

95% confidence interval

photos
Burner Rig 2D Cooling Effectiveness Maps

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

- \( M' = 0.291 \)
  - 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

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

Decay time temperature maps

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

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

95\% confidence interval

photos
Burner Rig 2D Cooling Effectiveness Maps

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

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

Initially increasing air film cooling effectiveness

Increasing through-hole convection cooling effectiveness

Slowly decreasing air film cooling effectiveness

Slowly increasing backside impingement cooling effectiveness

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

\begin{tabular}{cccc}
M' = 0 & M' = 0.209 & M' = 0.314 & M' = 0.654 & M' = 0.785 \\
\end{tabular}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{burner_rig_temperature_maps.png}
\caption{Burner Rig 2D Temperature Maps}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{burner_rig_decay_time_temperature_maps.png}
\caption{Decay time temperature maps}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{burner_rig_95_percent_confidence_interval.png}
\caption{95\% confidence interval}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{burner_rig_photos.png}
\caption{Photos}
\end{figure}
Effect of Surface Deposition/Fouling

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

**Pre-fouling**

- $M' = 0.512$

**Post-fouling**

- $M' = 0.483$

- $M' = 0$

Decay time temperature maps

95% confidence interval

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:

\[ \eta' = \frac{T^{\text{surface cooled}} - T^{\text{surface uncooled}}}{T^{\text{surface uncooled}} - T_{\text{coolant enter}}} \]

Metal cooling effectiveness from doped YSZ layer:

\[ \Phi' = \frac{T^{\text{metal cooled}} - T^{\text{metal uncooled}}}{T^{\text{metal uncooled}} - T_{\text{coolant enter}}} \]
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.