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.
Mainstream Hot Gas Flow

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

Heat flux across TBC:

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

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

$T_{\text{mainstream}}$

$T_{\text{air film}}$

$T_{\text{coolant gas}}$

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

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

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

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

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:

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

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:

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

- 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:

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

- 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.

\[
\Phi_{\text{overall}} > \Phi_{TBC}, \Phi_{\text{airfilm}} \quad (\text{TBC, air film cooling always beneficial})
\]

- 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
- 3.175 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, $\eta$
  \[ \eta = \frac{T_{\text{mainstream}} - T_{\text{adiabatic}}}{T_{\text{mainstream}} - T_{\text{coolant exit}}} \]
- $\eta$ 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)

532 nm excitation
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
$n = 64$
$t_0 = 0.1 \, \mu s$
$\Delta t =$ 0.25 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).

Individual Pixel Decays

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

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

Find \( T \) that gives know \( \tau \) where \( \tau = \tau_2^{R} \frac{1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta E + \Delta E) / kT}} \)

Temperature Map

Temperature Line Scan

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

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

Intensities and Wavelengths:
- CH*: 392nm
- C2*: 430nm, 514nm, 560nm, 514nm, 750nm
- CO2*: + soot broadband
- Specimen thermal radiation broadband

Background Radiation Sources:
- Surface Thermal & Reflected Combustor Radiation

Sample Images:
- 23% air, 27% fuel
- 30% air, 17% fuel
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 \( I = I_0 e^{-t/\tau} \)

\( \tau = 31.3 \mu s \)

\( \tau = 43.3 \mu s \)

\( \tau = 52.8 \mu s \)
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

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

1 cm

Image Stack

\( 0 \mu s \)

1 cm

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

$M' = 0.097$

$M' = 0.291$

$M' = 0.512$

$M' = 0.724$

$M' = 0.789$

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

95% confidence interval

photos

900 °C

850

800

750

700

650

30 °C

25

20

15

10

5

0
Burner Rig 2D Cooling Effectiveness Maps

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

$\eta' = 0.291$

Initially increasing air film cooling effectiveness

$\eta' = 0.369$

Slowly increasing backside impingement cooling effectiveness

$\eta' = 0.512$

Vortex-induced hot spot

$\eta' = 0.629$

Rapidly increasing through-hole convection cooling effectiveness

$\eta' = 0.724$

Diminishing air film cooling effectiveness

$\eta' = 0.789$

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
M' = 0.302
M' = 0.503
M' = 0.755
M' = 0.880

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

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

- $M' = 0.503$

- $M' = 0.629$

- $M' = 0.755$

- $M' = 0.880$
  - 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

\[ M' = 0 \quad M' = 0.209 \quad M' = 0.314 \quad M' = 0.654 \quad M' = 0.785 \]

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

95% confidence interval

photos
Effect of Surface Deposition/Fouling

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

Pre-fouling

Post-fouling

$M' = 0.512$

$M' = 0.483$

Decay time temperature maps

1 cm

95% confidence interval

Deposition/fouling does not bias temperature measurement but does reduce measurement precision.

Fouling changes emissivity

$M' = 0$
**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

$T_{\text{mainstream}}$  

$T_{\text{air film}}$  

$T_{\text{surface}}$  

Cr:GAP  

Doped YSZ Phosphor  

$T_{\text{metal}}$  

Surface cooling effectiveness from Cr:GAP layer:

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

Metal cooling effectiveness from doped YSZ layer:

$$\Phi' = \frac{T_{\text{metal}}^{\text{uncooled}} - T_{\text{metal}}^{\text{cooled}}}{T_{\text{coolant enter}}^{\text{uncooled}} - T_{\text{coolant enter}}^{\text{cooled}}}$$
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.