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

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

Heat flux across TBC:

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

Fixed \( q \) drives heat transport.

Thermal protection:

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

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

Mainstream Gas Flow

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

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

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

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

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

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

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

\[ T_{\text{air film}} \]

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:

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

(1)

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:

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

- 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:

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

- 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.

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

![Graph showing temperature dependence of luminescence emission with 532 nm excitation]
Luminescence Decay Curves Obtained by Time-Gated Imaging
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 1$^{st}$ 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
$n = 64$
$t_0 = 0.1$ 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).

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

\[
\tau = \tau^R_{2E} \frac{1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta q + \Delta E)/kT}}
\]
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

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

Intensity (arb.units)
Wavelength nm

- C2* 514nm
- C2* 560nm
- CO2* + soot 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
\[ I_{ij}(\text{frame 1}) < 3200 \]

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

- $\tau = 31.3 \mu s$
- $\tau = 43.3 \mu s$
- $\tau = 52.8 \mu s$
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

Fit to \( \tau = \tau_{2E}^R \frac{1+3e^{-\Delta E/kT}}{1+\alpha e^{-\Delta E/kT} + \beta e^{-(\Delta E q + \Delta E)/kT}} \)

Removing Flame Burst Outliers
Effect of Luminous Flame Bursts

Decay time temperature maps 95% confidence interval

includes outlier pixels

excludes outlier pixels

$T_{\text{excluded}} - T_{\text{included}}$

$1 \text{ cm}$

Image Stack

$0 \mu s$

$1 \text{ cm}$
$I_{ij}(t_n)$ 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

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

\[ \text{\(1\ cm\)} \]

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

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

Decay time temperature maps

$M' = 0.101$

$M' = 0.302$

$M' = 0.503$

$M' = 0.755$

$M' = 0.880$

\(\pm 1\ cm\)

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
- Slowly increasing backside impingement cooling effectiveness
- Initially increasing air film cooling effectiveness

- \( M' = 0.503 \) M' = 0.629 M' = 0.755 M' = 0.880
- Increasing through-hole convection cooling effectiveness
- Slowly decreasing air film cooling effectiveness
- Weaker vortex-induced hot spot

1 cm
Burner Rig 2D Temperature Maps

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

Compromised by surface fouling and plenum leak

Decay time temperature maps

$M' = 0$
$M' = 0.209$
$M' = 0.314$
$M' = 0.654$
$M' = 0.785$

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

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**

\[ M' = 0.483 \]

Fouling changes emissivity

1 cm

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.
Surface cooling effectiveness from Cr:GAP layer:

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

Metal cooling effectiveness from doped YSZ layer:

$$\Phi' = \frac{T_{metal} - T_{metal}}{T_{uncooled} - T_{cooled}}$$
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.