Cooling Effectiveness Measurements for Air Film Cooling of Thermal Barrier Coated Surfaces in a Burner Rig Environment Using Phosphor Thermometry

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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 Turbine Blade/Vane

Mainstream Gas Flow

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

Coolant gas

\[ T_{\text{co}} \]

**Cooling effectiveness:**

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

- Air film cooling greatly reduces effective \( h_{\text{conv}} \) and therefore greatly reduces \( \Phi_{\text{TBC}} \)
- Air film cooling greatly reduces \( q \) and therefore \( \Delta T_{\text{TBC}} \)

- Experimental measurements of combined TBC + air film cooling effectiveness are needed to evaluate TBC/air-film-cooling tradeoffs (Air film cooling carries significant penalty for engine efficiency).
Objectives

• Experimentally map effectiveness of air film cooling on TBC-coated surfaces.

• 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 with scaled up simple cooling hole geometry.
  - Initial testing of actual vane component did not produce effective air film cooling.

- 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 enables 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. ✓
  - Only applicable to steady state temperatures. ✗
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:
- 6.35 mm
- 125 μm
- 200 μm
- 30 μm

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

EB-PVD
Cooling Effectiveness Measurements

Conventional Air Film Cooling Effectiveness Test

- Uniform mainstream flow (velocity & temperature)
- Typical surface temperatures: < 100°C
- 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 pure 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
- 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 \( M' \)
  \[ M' = \frac{\rho_{\text{coolant}} v_{\text{coolant}}}{\rho_{\text{mainstream}} v_{\text{mainstream}}^{\text{max}}} \]
2D Temperature Mapping by Luminescence Lifetime Imaging

- Image stack collection
- Background subtraction
- Data filtering
- Pixel by pixel lifetime analysis
- Produce temperature and cooling effectiveness maps from decay time maps
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 radiation background from each frame collected.
  - Step 2: Assemble stack of background-corrected time-gated images over sequence of incremented delay times.
  - Step 3: Perform pre-fit filtering.
Pre-Fit Data Filtering
Criteria for removing pixels unsuitable for temperature determination

Minimum absolute threshold
\[ I_{ij}(\text{frame 1}) < 2200 \]

Maximum final frame relative 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 < 6

Insufficient signal
Too cold: need to extend to longer delay times after laser pulse
Too hot: need smaller increments of delay time

Post-fit temperature map

Example of better delay time range & increments
2D Temperature Maps from Luminescence Lifetime Imaging

- Step 4: Fit luminescence decay curve at each pixel to produce decay time map. Dynamic fitting window spans region between 60% and 10% of initial intensity. (Matlab routine).

- Step 5: Use calibration data to convert decay time map to temperature map (Matlab routine).

\[ \tau = \tau_R e^{-\Delta E / kT} \]

Find \( T \) that gives know \( \tau \) where \( \tau = \tau_R e^{-\Delta E / kT} \)

Temperature Map

Temperature Line Scan

95% Confidence Interval
Burning particles crossing field of view produce temperature map artifacts, can be mitigated by outlier removal.

Luminous flame streaks produce local temperature errors ~20°C too low.

Decay time temperature maps include outlier pixels. Includes outlier pixels. Excludes outlier pixels. 95% confidence interval includes outlier pixels.

T_{\text{included}} - T_{\text{excluded}}
$I_{ij}(t_n)$ is intensity of pixel $ij$ in frame $n$ of stack,

$t_n = n \Delta t + t_0$ where $\Delta t$ is frame interval and $t_0$ is 1st frame time;

$I_{ij}(t_n)$ is an outlier when

$$\left| I_{ij}(t_n) - I_{ij}^{fit}(t_n) \right| > 1.5\sigma \left[ I_{ij}(t_n) - I_{ij}^{fit}(t_n) \right]$$
Air Film Cooling of TBC-Coated Surface

Results

• Examine changes in cooling effectiveness as a function of:
  – Mainstream hot gas temperatures: 1390, 1604, and 1722°C
  – Blowing ratio: $M'$ = 0 to 1.1
Burner Rig 2D Temperature Maps

\[ T_{\text{mainstream}} = 1390^\circ C \]

Decay time temperature maps

- \( M' = 0.134 \)
- \( M' = 0.321 \)
- \( M' = 0.535 \)
- \( M' = 0.803 \)
- \( M' = 0.936 \)

95\% confidence interval

Temperature Line Scan

Vortex-induced hot streaks

Distance (mm)

Temperature (°C)
Burner Rig 2D Cooling Effectiveness Maps

\[ T_{\text{mainstream}} = 1390^\circ \text{C} \]

- \( M' = 0.134 \)
- \( M' = 0.214 \)
- \( M' = 0.321 \)
- \( M' = 0.428 \)
- \( M' = 0.535 \)
- \( M' = 0.669 \)
- \( M' = 0.803 \)
- \( M' = 0.936 \)

Initially increasing air jet film cooling effectiveness

Rapidly increasing through-hole convection cooling effectiveness

Diminishing air film cooling effectiveness with air jet lift-off

Appearance of vortex-induced hot streaks

Cooling Effectiveness Line Scan

Vortex-induced hot streaks

Upstream through-hole convective cooling

\( \eta' \)

Distance (mm)

1 cm
Burner Rig 2D Temperature Maps

$T_{\text{mainstream}} = 1604^\circ\text{C}$

Decay time temperature maps

$M' = 0.151$

$M' = 0.362$

$M' = 0.604$

$M' = 0.906$

$M' = 1.057$

95% confidence interval

photos
Burner Rig 2D Cooling Effectiveness Maps

$T_{\text{mainstream}} = 1604^\circ\text{C}$

- $M' = 0.151$
- $M' = 0.242$
- $M' = 0.362$
- $M' = 0.483$
- $M' = 0.604$
- $M' = 0.755$
- $M' = 0.906$
- $M' = 1.057$

Initially increasing air jet film cooling effectiveness

Rapidly increasing through-hole convection cooling effectiveness

Diminishing air film cooling effectiveness with air jet lift-off

Appearance of vortex-induced hot streaks

Upstream through-hole convective cooling
Burner Rig 2D Temperature Maps

\[ T_{\text{mainstream}} = 1722^\circ \text{C} \]

Decay time temperature maps

\[ M' = 0.151 \quad M' = 0.385 \quad M' = 0.642 \quad M' = 0.963 \quad M' = 1.123 \]

95\% confidence interval

photos
Burner Rig 2D Cooling Effectiveness Maps

\[ T_{\text{mainstream}} = 1722°C \]

- \( M' = 0.160 \)
- \( M' = 0.257 \)
- \( M' = 0.385 \)
- \( M' = 0.514 \)
- \( M' = 0.642 \)
- \( M' = 0.802 \)
- \( M' = 0.963 \)
- \( M' = 1.123 \)

Initially increasing air jet film cooling effectiveness

Rapidly increasing through-hole convection cooling effectiveness

Diminishing air film cooling effectiveness with air jet lift-off

Appearance of vortex-induced hot streaks

Deposition/fouling region

Signal attenuation due to flame deposit
• **Air film cooling**
  – Effectiveness initially increases with increasing $M$, then diminishes with jet lift-off.
  – Vortex-induced hot streaks appear near cooling holes. 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 $M$.

• **Cooling effectiveness shows similar dependence on blowing ratio over wide range of mainstream gas temperature.**

• **Effect of TBC on other cooling mechanisms**
  – Will decrease air film cooling effectiveness.
  – Will increase through hole convective cooling effectiveness – may be useful for showerhead cooling.
Mainstream Gas Flow

Surface cooling effectiveness from Cr:GAP layer:

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

Metal cooling effectiveness from doped YSZ layer:

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

• 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

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