Temperature Mapping of Air Film-Cooled Thermal Barrier Coated Surfaces Using Phosphor Thermometry

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Aerial View of NASA Glenn Research Center
Cleveland, Ohio

We predate the space age!

1941 Groundbreaking

- National Advisory Committee for Aeronautics (NACA) Flight Propulsion Laboratory
- NASA Lewis Research Center (1958)
- NASA John H. Glenn Research Center (1999)
GRC is Northernmost of 10 NASA Centers

- **NASA**
  - De-icing research

- **Science**
  - Michelson-Morley experiment 1887

- **Technology**
  - First traffic light 1917

- **Sports**
  - Basketball champions (NBA) 2017

Cleveland highlights
Thermal Barrier Coatings (TBCs) Provide Thermal Protection for Gas Turbine Engine Components

- Ceramic oxide TBCs, e.g., yttria-stabilized zirconia, can increase engine temperatures, reduce cooling, lower emission, and improve engine efficiency and reliability.

- TBCs provide thermal protection by sustaining a thermal gradient between the TBC surface and underlying metal component.

(a) without TBC
(b) with current TBC
(c) with improved TBC
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

$T_{\text{mainstream}}$ → $T_{\text{air film}}$ → $T_{\text{metal}}$

$d_{TBC}$ → $\Delta T_{\text{surface convection}}$ → $\Delta T_{\text{backside convection}}$

$d_{\text{metal}}$

$T_{\text{coolant gas}}$

Cooling effectiveness:

$\Phi = \frac{T_{\text{mainstream}} - T_{\text{metal}}}{\Delta T_{\text{total}}}$

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

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

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

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.

Cr:GAP coated vane with cooling air supply tubing

Surface temperature maps of stator vane doublet in Mach 0.3 burner rig

- Increase air flow through cooling holes
- Dominated by backside impingement 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.
Luminescence Lifetime Image Stack

$n$ images
$t_0 = \text{start of 1}\text{st exposure}$
$\Delta t = \text{frame interval}$
$t_n = (n-1)\Delta t + t_0$
$= \text{delay time after laser pulse for } n\text{th image in stack}$

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)
Luminescence Decay Curves from 25 μm GAP:Cr Coating in Furnace
Time-Gated Imaging Averaged over 184x154 Pixel Area
Extracted from 64-Frame Stacks

Fit to $I = I_0 e^{-t/\tau}$
Calibration of Decay Time vs. Temperature for Cr:GAP 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 \( \tau = \tau_2^R \frac{1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta E + \Delta E)/kT}} \)

Cooling Hole Plate Geometry

Side view:
- 6.35 mm width
- 30° angle

Top view:
- 76.4 mm height
- 50.8 mm length
- 3.175 mm gap
- 9.525 mm gap

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

EB-PVD
Cooling Effectiveness Measurements

**Conventional Air Film Cooling Effectiveness Test**
- Ducted uniform mainstream flow

- Uniform mainstream flow (velocity & temperature)
- Typical surface temperatures: < 100°C
- Measure adiabatic air film cooling effectiveness, $\eta = \frac{T_{\text{mainstream}} - T_{\text{adiabatic}}}{T_{\text{mainstream}} - T_{\text{surface}}}$
- $\eta$ 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**
- Diverted unducted divergent mainstream flow

- 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 $M'$

\[ M' = \frac{\rho_{\text{coolant}} v_{\text{coolant}}}{\rho_{\text{mainstream}} v_{\text{mainstream}}^{\text{max}}} \]
Burner Rig Plenum Geometry

Expanded laser beam coverage of plate

burner

ICCD

laser

pyrometer

burner
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
Pre-Fit Data Filtering
Criteria for removing pixels unsuitable for temperature determination

- Minimum absolute threshold: $l_{ij}(\text{frame 1}) < 2200$
- Maximum final frame relative threshold: $l_{ij}(\text{last frame}) > 10\% l_{ij}(\text{first frame})$
- Minimum number of frames in fitting interval: $10\% l_{ij}(\text{first frame}) < l_{ij}(\text{frame n}) < 90\% l_{ij}(\text{first frame})$
- 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

- Multi-step procedure:
  - Step 1: Remove radiation background from each frame collected.

Luminescence before background subtraction  |  Background (no laser)  |  Luminescence after background subtraction

10 µs exposure 300 µs after laser pulse

- Step 2: Assemble stack of background-corrected time-gated images over sequence of incremented delay times.

- Step 3: Preform pre-fit filtering.
  - Insufficient intensity, decay too fast or too slow
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).

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

$$\tau = \tau^R_2 \frac{1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta E + \Delta E)/kT}}$$

Temperature Map

Temperature Line Scan

95% Confidence Interval
Burning particles crossing field of view produce temperature map artifacts, can be mitigated by outlier removal.
$I_{ij}(t_n)$ 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 $|I_{ij}(t_n) - I_{ij}^{\text{fit}}(t_n)| > 1.5\sigma [I_{ij}(t_n) - I_{ij}^{\text{fit}}(t_n)]$
Air Film Cooling of TBC-Coated Surface
Results

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

$T_{\text{mainstream}} = 1390^\circ\text{C}$

Decay time temperature maps

$M' = 0.134$

$M' = 0.321$

$M' = 0.535$

$M' = 0.803$

$M' = 0.936$

1 cm

95% confidence interval

Temperature Line Scan

Vortex-induced hot streaks

photos
Burner Rig 2D Cooling Effectiveness Maps

$T_{\text{mainstream}} = 1390^\circ C$

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 Cooling Effectiveness Maps

\[ T_{\text{mainstream}} = 1604^\circ \text{C} \]

\[ M' = 0.151 \quad M' = 0.242 \quad M' = 0.362 \quad M' = 0.483 \]

Initially increasing air jet film cooling effectiveness

\[ M' = 0.604 \quad M' = 0.755 \quad M' = 0.906 \quad M' = 1.057 \]

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

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

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

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

M' = 0.160
M' = 0.257
M' = 0.385
M' = 0.514
M' = 0.642
M' = 0.802
M' = 1.123
How Many Frames Do We Really Need?
64 frames requires minimum 3 s, up to minutes at highest temperatures

2x binning

2x decimation

$n x$ binning = $n x$ faster acquisition

$n x$ decimation = $n x$ faster acquisition
\[ T_{\text{mainstream}} = 1390^\circ C \]
\[ M' = 0.321 \]

**Burner Rig 2D Temperature Maps**

**Effect of Binning**

- 64 frames (no binning)
- 32 frames (2x binning)
- 16 frames (4x binning)
- 8 frames (8x binning)

Decay time temperature maps

\[ 1 \text{ cm} \]

95% confidence interval

\[ \Delta T = T_{\text{binned}} - T_{\text{unbinned}} \]

\[ nx \text{ binning} = nx \text{ faster acquisition} \]

Binning effects
- Limits temperature range
- Modest decrease in precision
- Produces very little bias
Burner Rig 2D Temperature Maps

Effect of Binning

$T_{\text{mainstream}} = 1390^\circ \text{C}$

$M' = 0.321$

64 frames (no binning)

32 frames (2x binning)

32 frames (2x decimation)

Decay time temperature maps

1 cm

95% confidence interval

$\Delta T = T_{\text{binned}} - T_{\text{unbinned}}$

$n \times \text{binning} = n \times \text{faster acquisition}$

$T_{16} - T_{64}$

2x decimated minus 2x binned
**Combined Cooling Effects Summary**

- **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.
Future Direction
Add Metal Surface Temperature Maps

Mainstream Gas Flow

$T_{\text{mainstream}} \rightarrow \rightarrow \rightarrow \rightarrow T_{\text{air film}} \rightarrow T_{\text{surface}}$

Cr:GAP

Doped YSZ Phosphor

$T_{\text{coolant gas}}$

$T_{\text{metal}}$

$T_{\text{coolant enter}}$

Surface cooling effectiveness from Cr:GAP layer:

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

Metal cooling effectiveness from doped YSZ layer:

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