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

Cleveland highlights
- Science: Michelson-Morley experiment 1887
- Technology: First traffic light 1917
- Sports: Basketball champions (NBA) 2017

NASA
- De-icing research

Image of Glenn Research Center and map of the United States highlighting different NASA centers and 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

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

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

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

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

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

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

Cooling effectiveness:

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

- 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.
Luminescence Lifetime Image Stack

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

Typical values
\[ n = 64 \]
\[ t_0 = 0.1 \, \mu\text{s} \]
\[ \Delta t = 0.25 \text{ to } 100 \, \mu\text{s} \]
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:
- $200^\circ C < T < 750^\circ C$: less temperature sensitive
- $T > 750^\circ C$: 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 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, \( \eta \):
  \[
  \eta = \frac{T_{\text{mainstream}} - T_{\text{adiabatic}}}{T_{\text{mainstream}} - T_{\text{surface}}}
  \]
- \( \eta \) 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: \( l_{ij}(\text{last frame}) > 10\% \times l_{ij}(\text{first frame}) \)
- 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: \( < 6 \)

**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.

- 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).

Individual Pixel Decays

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

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

$$\tau = \frac{\tau_{2E}^R}{1 + 3e^{-\Delta E/kT} + \beta e^{-(\Delta E + \gamma E)/kT}}$$
Effect of Luminous Flame Bursts

Decay time temperature maps 95% confidence interval

Image Stack

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

includes outlier pixels

Luminous flame streaks produce local temperature errors \(-20^\circ\text{C}\) too low.

excludes outlier pixels

Burning particles crossing field of view produce temperature map artifacts, can be mitigated by outlier removal.
Effect of 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 $|I_{ij}(t_n) - I_{ij}^{\text{fit}}(t_n)| > 1.5\sigma[I_{ij}(t_n) - I_{ij}^{\text{fit}}(t_n)]$

$\tau = 140.1 \mu s$
(777.6°C)

$\tau = 84.3 \mu s$
(813.4°C)
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

$T_{\text{mainstream}} = 1390°C$

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 Temperature Maps

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

Decay time temperature maps

$M' = 0.151$

$M' = 0.362$

$M' = 0.604$

$M' = 0.906$

$M' = 1.057$

1 cm

95% confidence interval

photos
Burner Rig 2D Cooling Effectiveness Maps

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

Initially increasing air jet film cooling effectiveness

M' = 0.151
M' = 0.242
M' = 0.362
M' = 0.483

Rapidly increasing through-hole convection cooling effectiveness
Diminishing air film cooling effectiveness with air jet lift-off
Appearance of vortex-induced hot streaks

M' = 0.604
M' = 0.755
M' = 0.906
M' = 1.057

1 cm

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

$T_{\text{mainstream}} = 1722^\circ\text{C}$

Decay time temperature maps

$M' = 0.151$

$M' = 0.385$

$M' = 0.642$

$M' = 0.963$

$M' = 1.123$

1 cm

95% confidence interval

Photos
Burner Rig 2D Cooling Effectiveness Maps

$T_{\text{mainstream}} = 1722^\circ\text{C}$

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

$1\text{ cm}$
How Many Frames Do We Really Need?
64 frames requires minimum 3 s, up to minutes at highest temperatures

$n_x$ binning = $n_x$ faster acquisition

$n_x$ decimation = $n_x$ faster acquisition
Burner Rig 2D Temperature Maps
Effect of Binning

$T_{\text{mainstream}} = 1390^\circ C$
$M' = 0.321$

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

Decay time temperature maps
1 cm

95% confidence interval

$\Delta T = T_{\text{binned}} - T_{\text{unbinned}}$
$n\times$ binning = $n\times$ faster acquisition

Binning effects
- Limits temperature range
- Modest decrease in precision
- Produces very little bias
$T_{\text{mainstream}} = 1390^\circ \text{C}$

$M' = 0.321$

Burner Rig 2D Temperature Maps

Effect of Binning

64 frames (no binning)

32 frames (2x binning)

32 frames (2x decimation)

2x decimated minus 2x binned

Decay time temperature maps

1 cm

95% confidence interval

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

$n x$ binning = $n x$ faster acquisition
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
$T_{\text{mainstream}}$

$T_{\text{air film}}$

$T_{\text{surface}}$

$Cr:GAP$

Doped YSZ Phosphor

$T_{\text{coolant gas}}$

$T_{\text{metal}}$

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

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