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

Jeffrey I. Eldridge
NASA Glenn Research Center
Cleveland, Ohio
USA

Lund University
Combustion Physics Department
December 8, 2016
Acknowledgments

- NASA GRC
  - Michael Cuy (Burner rig testing)
  - Dongming Zhu (High heat flux testing)
  - Adam Wroblewski (Matlab-based image processing)
  - Vikram Shyam (Air-film cooling expertise)

- Penn State
  - Doug Wolfe (EB-PVD)

- Funding by NASA Fundamental Aero Transformational Tools & Technologies Project
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

De-icing research

Science: Michelson-Morley experiment 1887

Technology: First traffic light 1917

Sports: Basketball champions (NBA) 2017
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.
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

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

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

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

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

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

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

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

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

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

Cooling effectiveness:

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

- 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
$t_0 =$ 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)
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 $\tau = \frac{\tau_2^R}{1 + 3e^{-\Delta E/kT} + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta E + \Delta E)/kT}}$

Cooling Hole Plate Geometry

Side view:
- 6.35 mm
- 30°

Top view:
- 76.4 mm
- 50.8 mm
- 9.525 mm
- 3.175 mm

Coating layers:
- Cr:GAP
- YSZ
- MCrAlY
- 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, $\eta$
  \[ \eta = \frac{T_{\text{mainstream}} - T_{\text{adiabatic}}}{T_{\text{mainstream}} - T_{\text{coolant exit}}} \]
- $\eta$ 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**
- 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 $M'$
  \[ M' = \frac{\rho_{\text{coolant}} v_{\text{coolant}}}{\rho_{\text{mainstream}} v_{\text{mainstream}}} \]
Burner Rig Plenum Geometry

- Expanded laser beam coverage of plate
- Burner
- Laser
- PCI
- 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
\[ l_{ij}(\text{last frame}) > 10\% \cdot l_{ij}(\text{first frame}) \]

Minimum number of frames in fitting interval
\[ 10\% \cdot l_{ij}(\text{first frame}) < l_{ij}(\text{frame n}) < 90\% \cdot l_{ij}(\text{first frame}) \]

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

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

- Step 3: Perform 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](image1)

  - $\tau = 254 \mu s$ (727°C)
  - $\tau = 53 \mu s$ (843°C)

  ![Decay Time Map](image2)

  - 1 cm

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

  Find $T$ that gives $\tau$ where $\tau = \frac{\tau_R}{1 + (\alpha e^{-\Delta E/kT} + \beta e^{-(\Delta E + \Delta E)/kT})}$.
Effect of Luminous Flame Bursts

Decay time temperature maps  95% confidence interval

Image Stack

0 μsec

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

T_{included} - T_{excluded}

includes outlier pixels

excludes outlier pixels

Luminous flame streaks produce local temperature errors ~20°C too low.
$I_{ij}(t_n)$ 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 $|I_{ij}(t_n) - I_{ij}^{fit}(t_n)| > 1.5\sigma[I_{ij}(t_n) - I_{ij}^{fit}(t_n)]$
Air Film Cooling of TBC-Coated Surface Results

- Examine changes in cooling effectiveness as a function of:
  - Mainstream hot gas temperatures: 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
Burner Rig 2D Cooling Effectiveness Maps

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

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

Upstream through-hole convective cooling
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

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

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

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

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

Initially increasing air jet film cooling effectiveness

$M' = 0.160$
$M' = 0.257$
$M' = 0.385$
$M' = 0.514$

Rapidly increasing through-hole convection cooling effectiveness

$M' = 0.642$
$M' = 0.802$
$M' = 1.123$

Deposition/fouling region

Appearance of vortex-induced hot streaks

Signal attenuation due to flame deposit
How Many Frames Do We Really Need?
64 frames requires minimum 3 s, up to minutes at highest temperatures

2x binning

2x decimation

nx binning = nx faster acquisition

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

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

Decay time temperature maps

1 cm

95% confidence interval

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

nx binning = nx faster acquisition

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

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

Decay time temperature maps

ensor

95% confidence interval

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

\( nx \) binning = \( nx \) 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

\( T_{\text{coolant gas}} \)

Surface cooling effectiveness from Cr:GAP layer:

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

Metal cooling effectiveness from doped YSZ layer:

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