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

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  - Michael Cuy (Burner rig testing)
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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

NASA
De-icing research

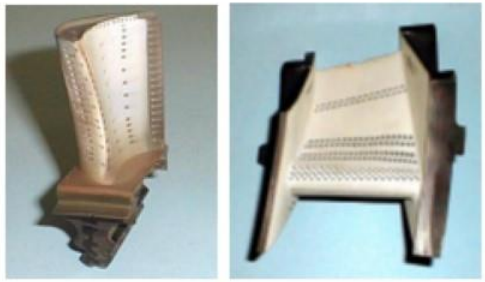
Science
Michelson-Morley experiment
1887

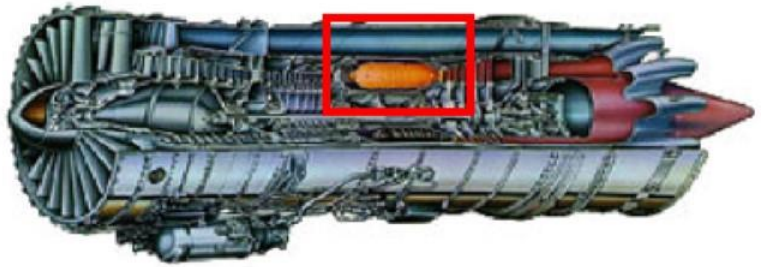
Technology
First traffic light
1917

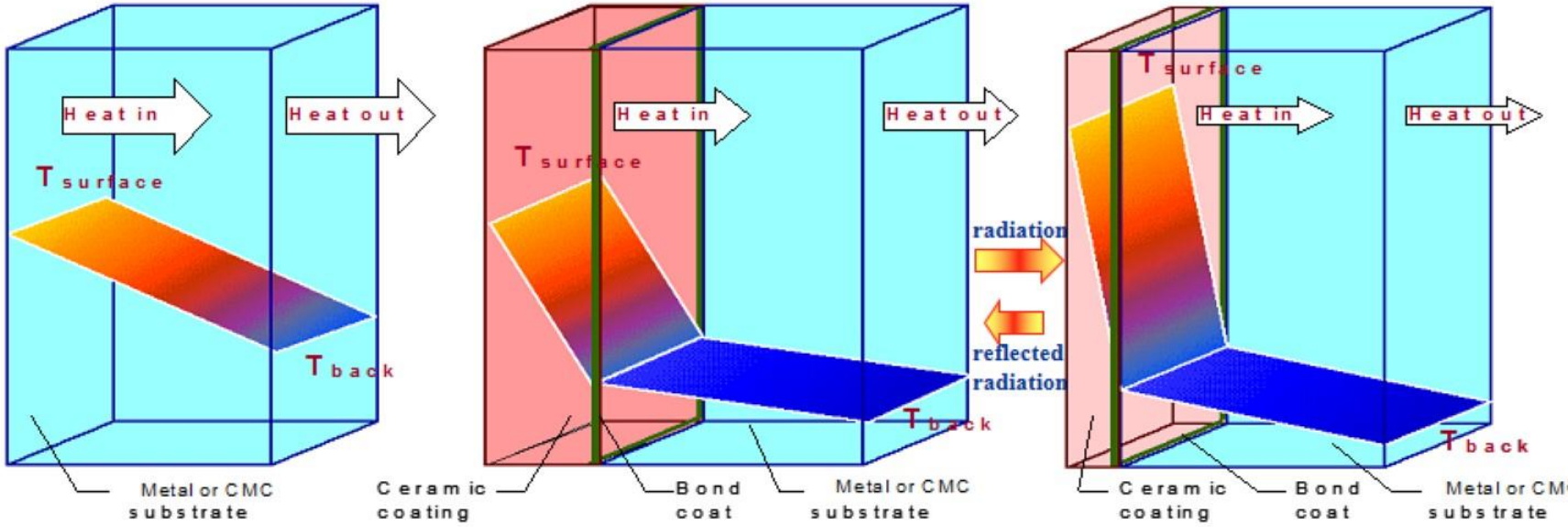
Sports
Basketball champions (NBA)
2017

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.





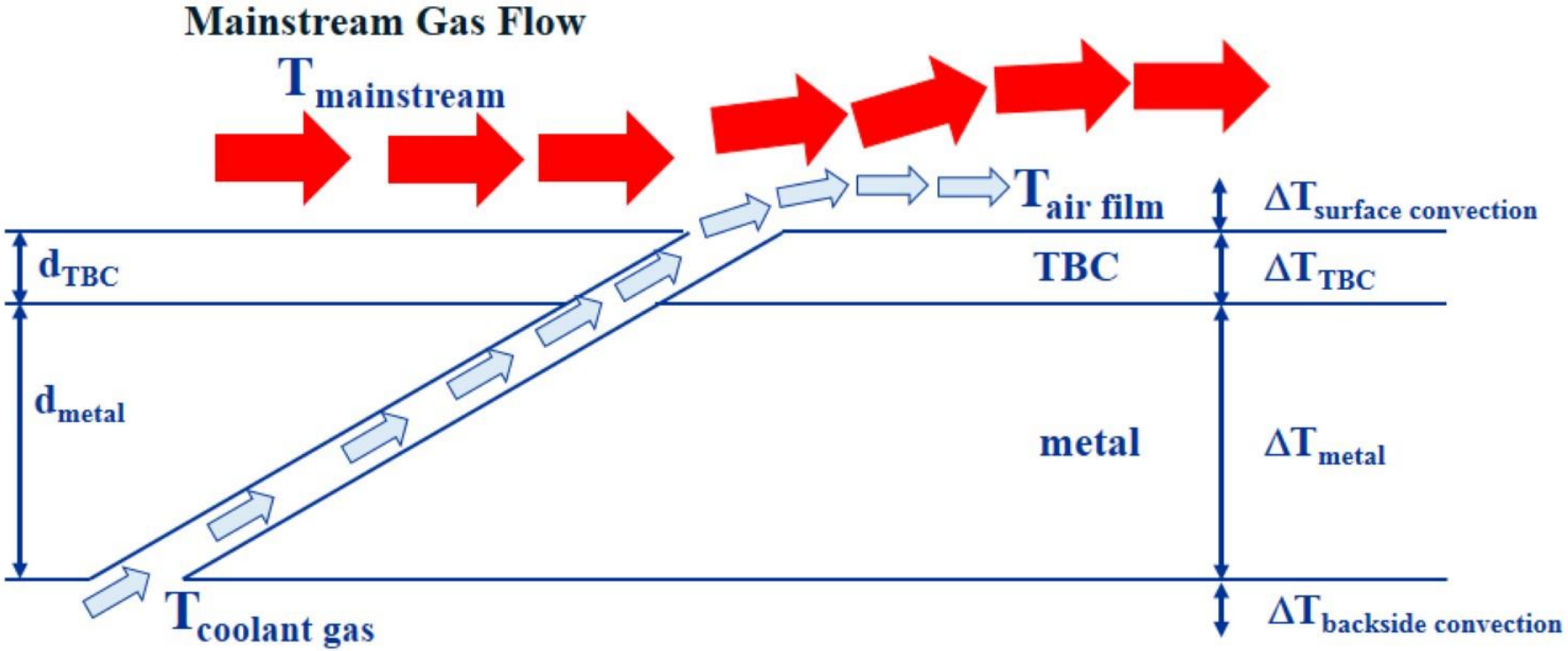


(a) without TBC (b) with current TBC (c) with improved TBC

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



Cooling effectiveness: (fraction of ΔT_{total} that occurs above metal surface)

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

- Air film cooling greatly reduces effective h_{conv} and therefore greatly reduces Φ_{TBC}
- Air film cooling greatly reduces q and therefore ΔT_{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).

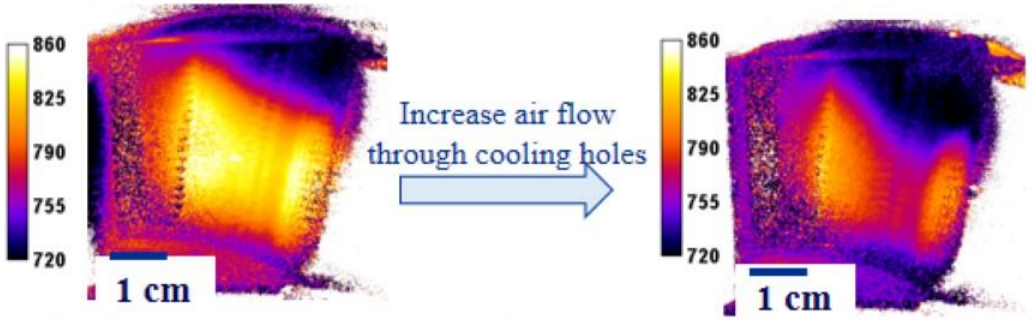
Objectives

- 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.

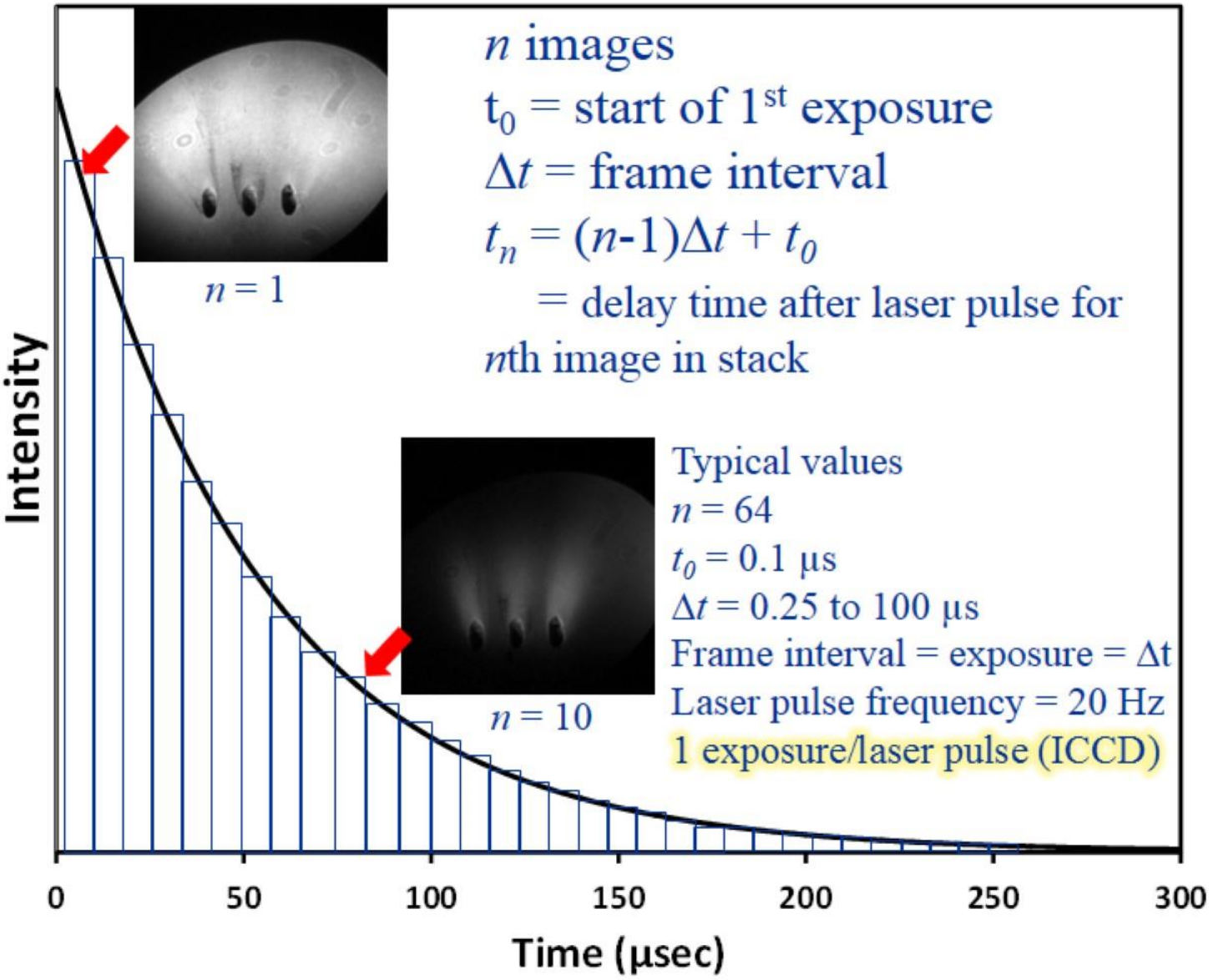
Cr:GAP coated vane with cooling air supply tubing



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

- 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. ✗

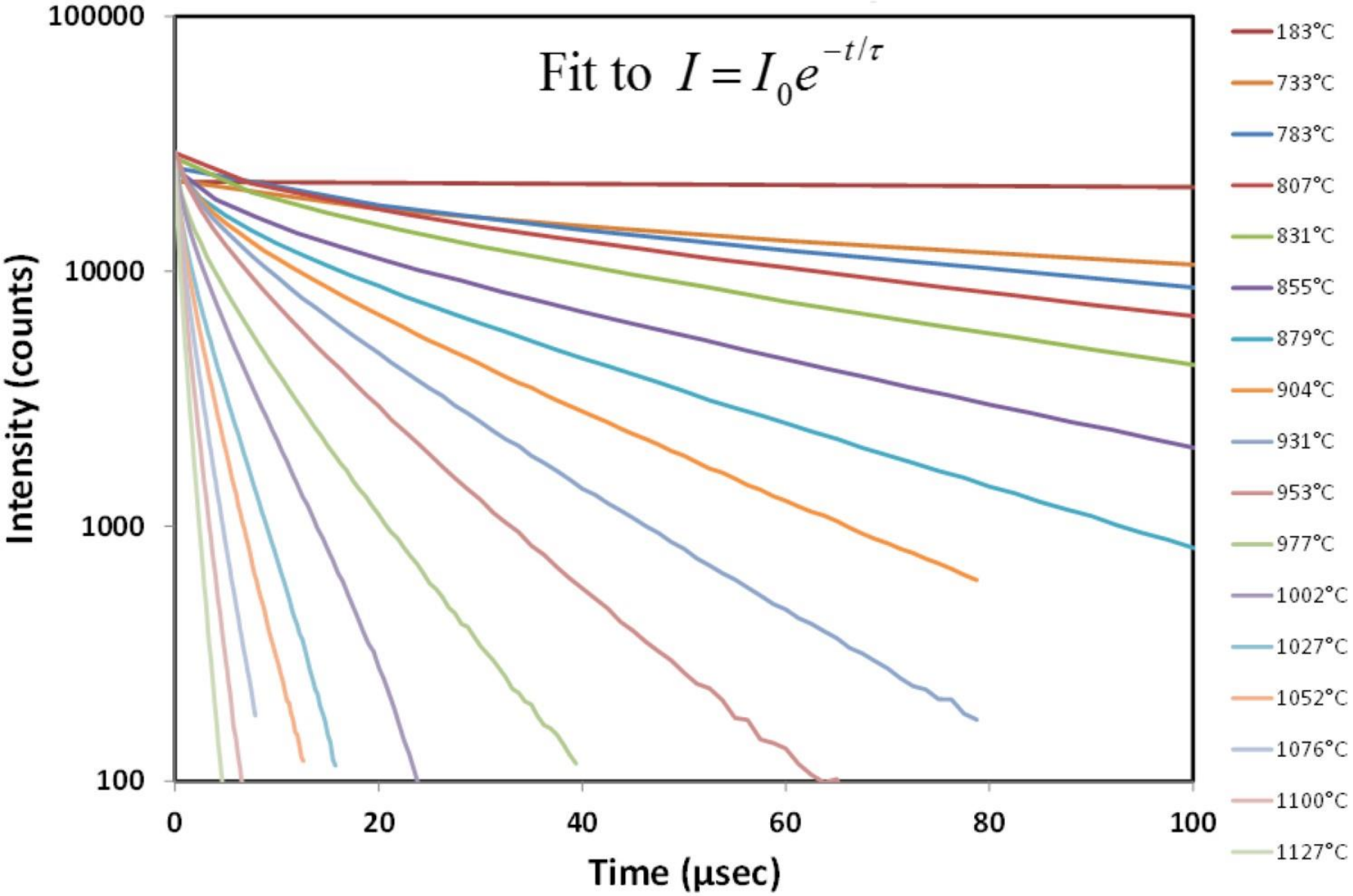
Luminescence Lifetime Image Stack



Luminescence Decay Curves from 25 µm GAP:Cr Coating in Furnace

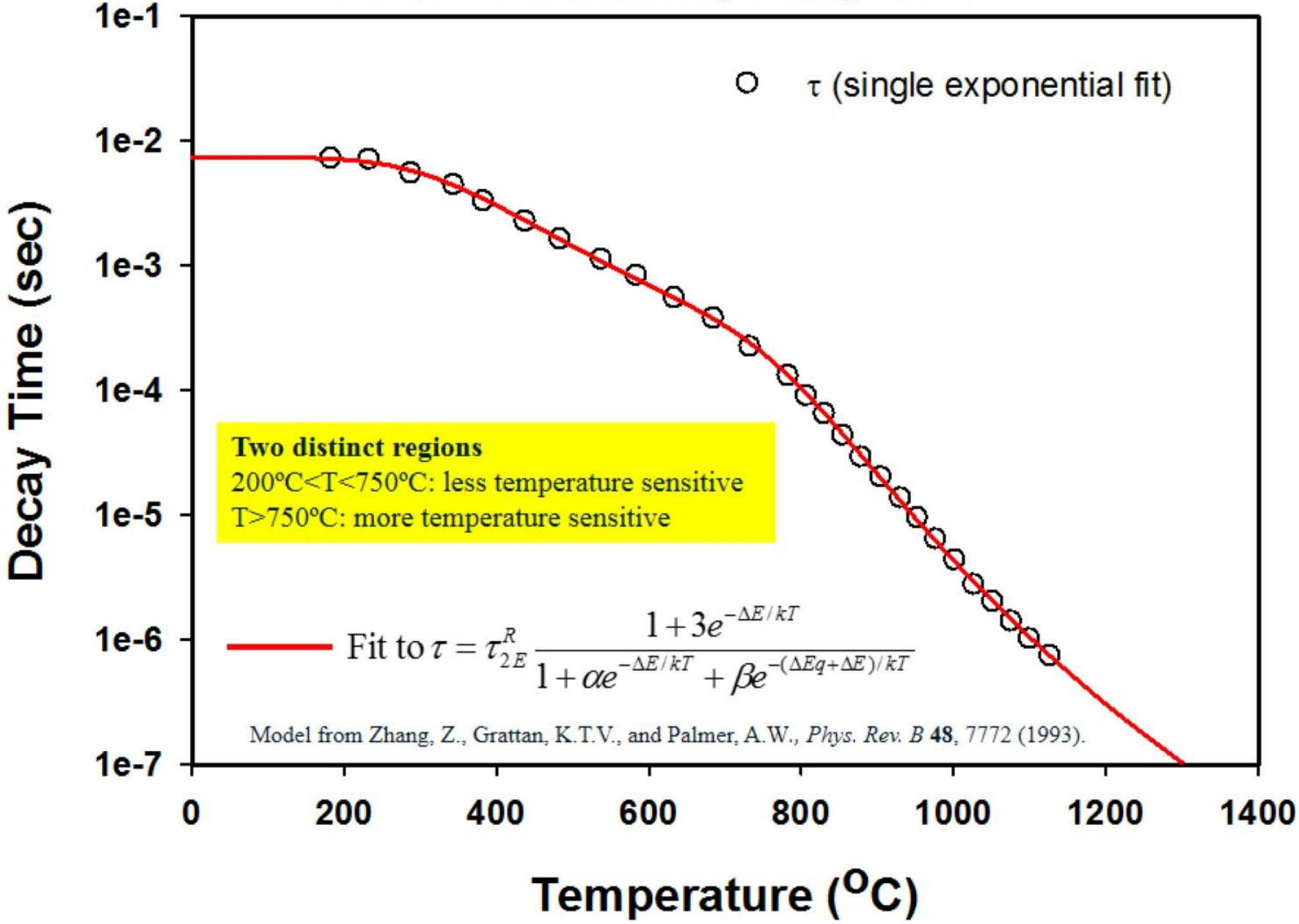
Time-Gated Imaging Averaged over 184x154 Pixel Area

Extracted from 64-Frame Stacks

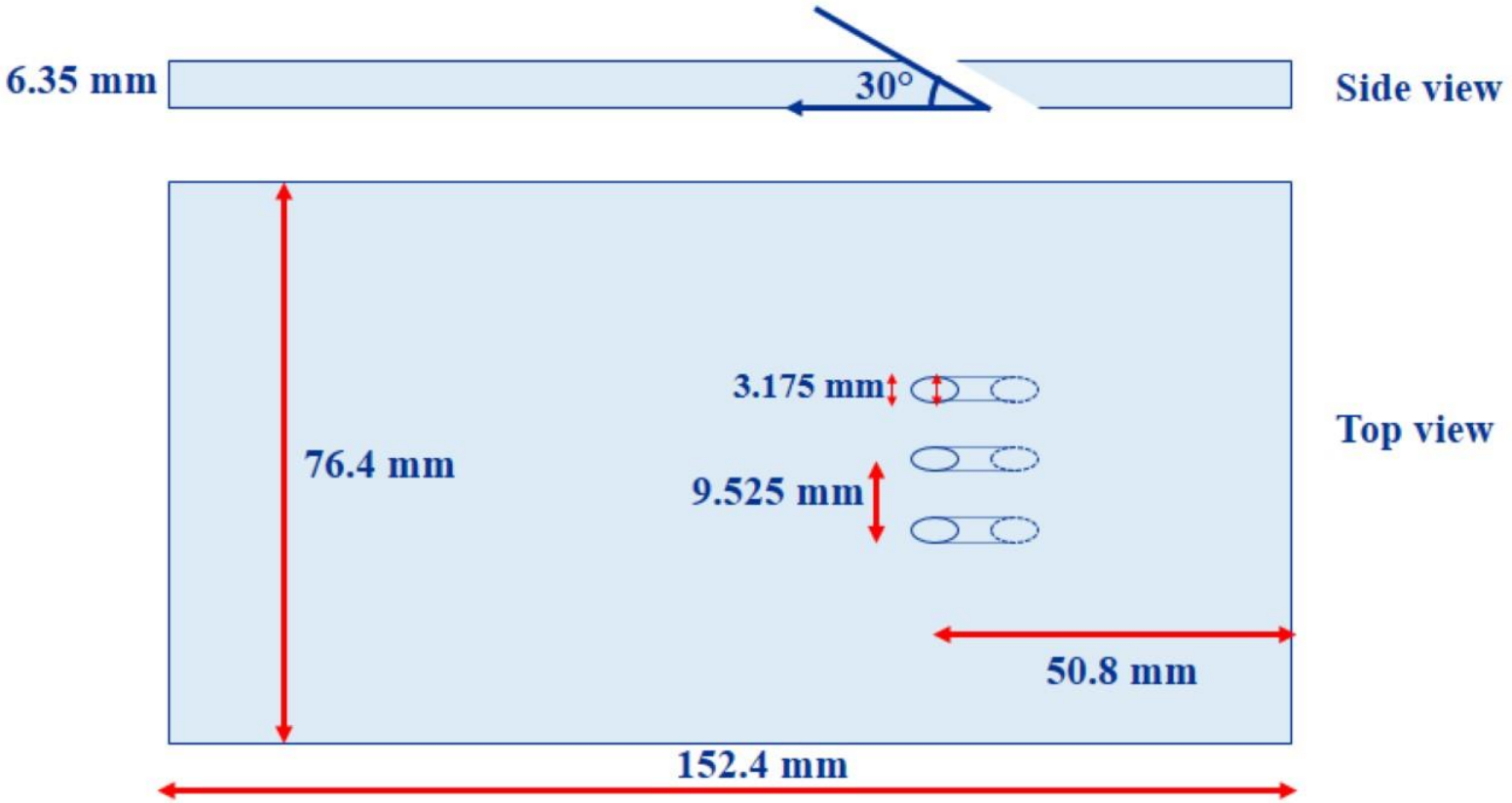


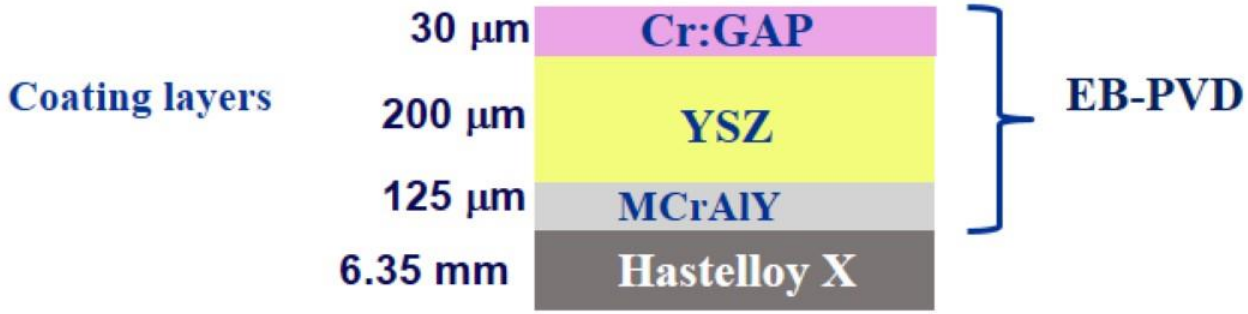
Calibration of Decay Time vs. Temperature for Cr:GAP Coating

60 to 10% Initial Intensity Fitting Window



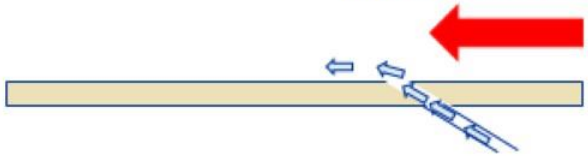
Cooling Hole Plate Geometry

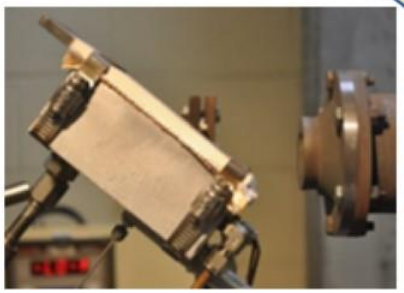




Cooling Effectiveness Measurements

Conventional Air Film Cooling Effectiveness Test





- Uniform mainstream flow (velocity & temperature)
- Typical surface temperatures: < 100°C
- Measure adiabatic air film cooling effectiveness, η

$$\eta = \frac{T_{mainstream} - T_{surface}^{adiabatic}}{T_{mainstream} - T_{coolant\ exit}}$$

- η is a fundamental characterization of pure air film cooling effectiveness
- Measure η as a function of blowing ratio, M

$$M = \frac{\rho_{coolant} v_{coolant}}{\rho_{mainstream} v_{mainstream}}$$

Burner Rig Air Film Cooling Effectiveness Test

- Divergent mainstream flow
- Typical temperatures: 600-1100°C
- Measure overall surface cooling effectiveness, η'

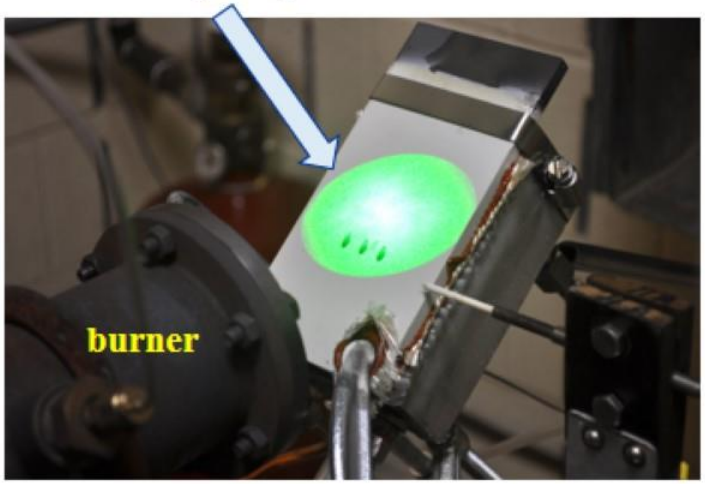
$$\eta' = \frac{T_{uncooled} - T_{cooled}}{T_{uncooled} - T_{coolant\ enter}}$$

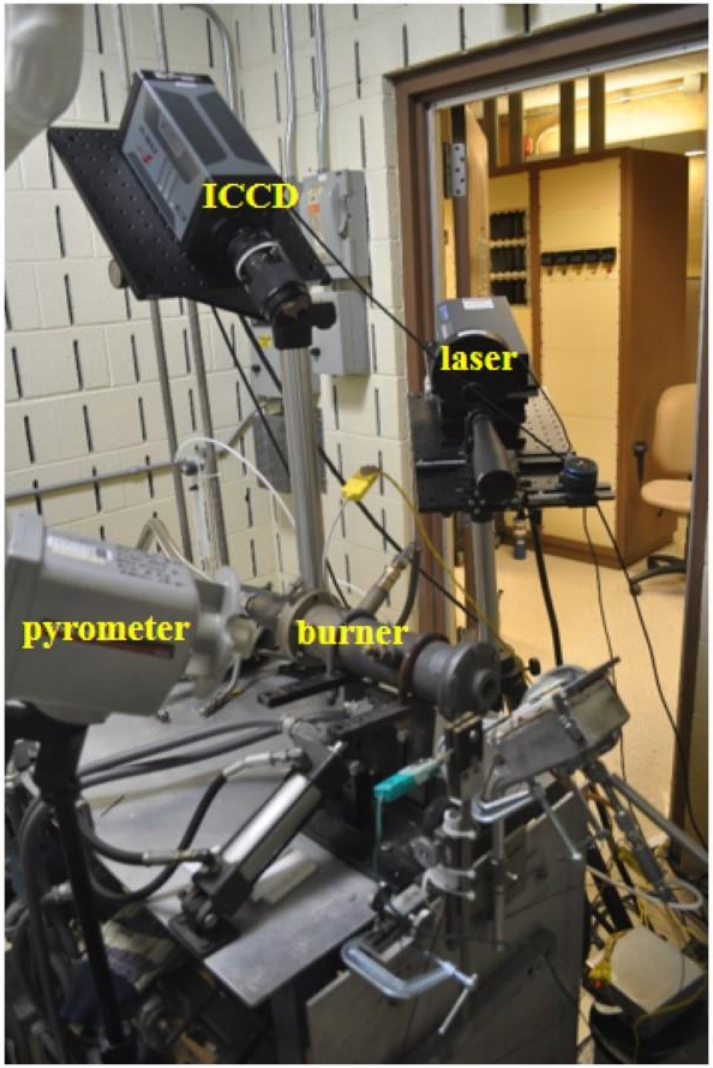
- η' is a nonfundamental but realistic characterization of combined surface cooling effects
- Measure η' as a function of M

$$M' = \frac{\rho_{coolant} v_{coolant}}{\rho_{mainstream} v_{mainstream}^{max}}$$

Burner Rig Plenum Geometry

Expanded laser beam coverage of plate





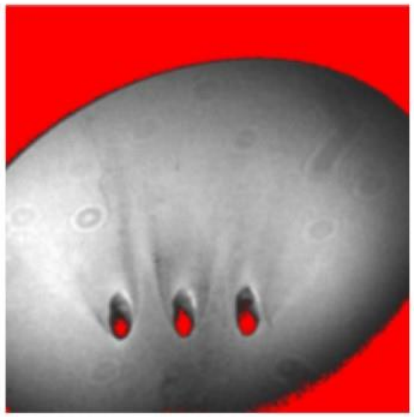
2D Temperature Mapping by Luminescence Lifetime Imaging

- 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

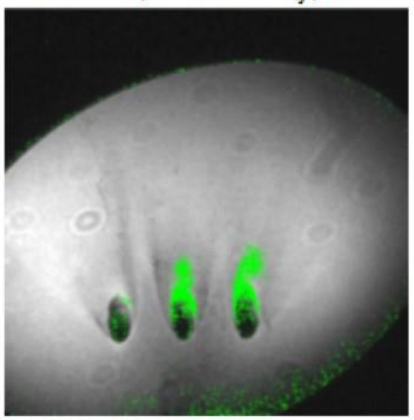
Criteria for removing pixels unsuitable for temperature determination

Minimum absolute threshold
I_{ij}(frame 1) < 2200



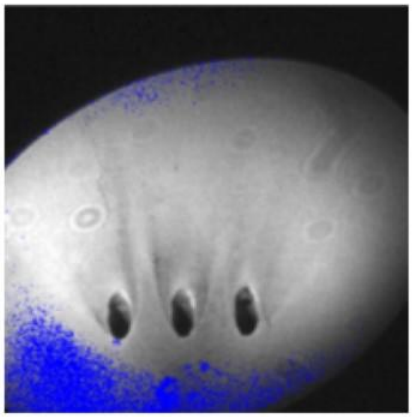
Insufficient signal

Maximum final frame relative threshold
I_{ij}(last frame) > 10%*I_{ij}(first frame)



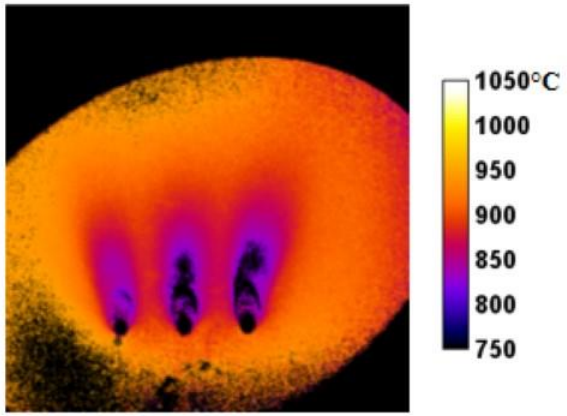
Too cold: need to extend to longer delay times after laser pulse

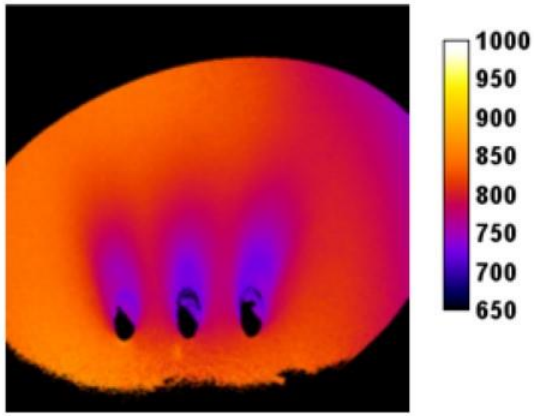
Minimum number of frames in fitting interval
10%*I_{ij}(first frame) < I_{ij}(frame n) < 90%*I_{ij}(first frame)
Number of frames < 6



Too hot: need smaller increments of delay time

Post-fit temperature map

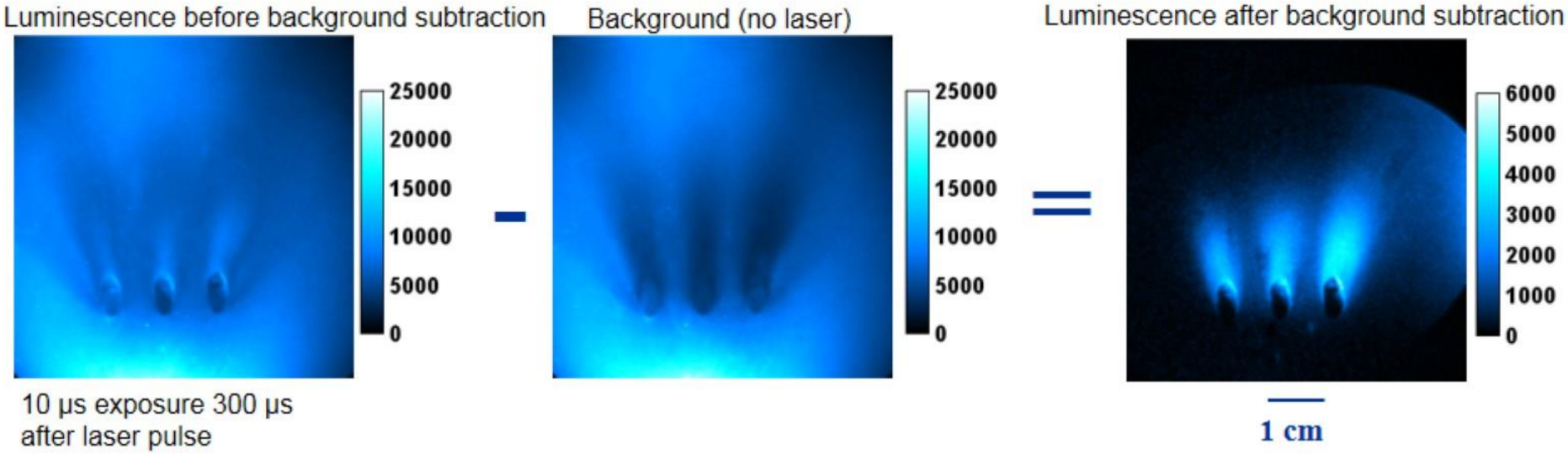




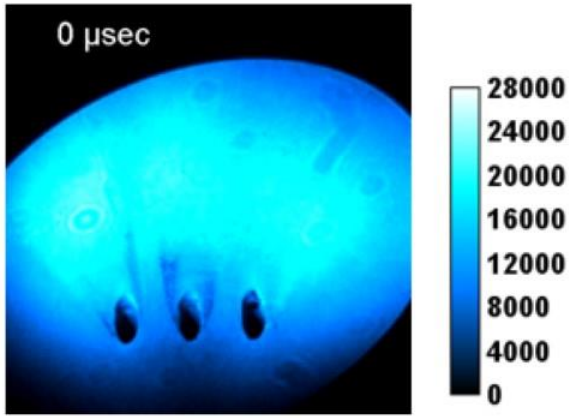
Example of better delay time range & increments

2D Temperature Maps from Luminescence Lifetime Imaging

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



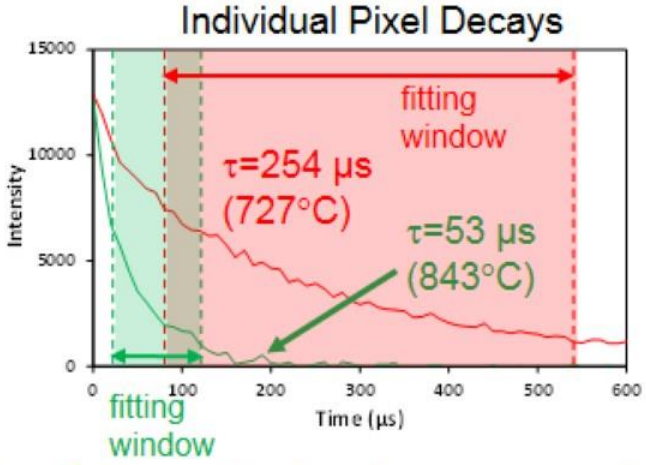
  - Step 2: Assemble stack of background-corrected time-gated images over sequence of incremented delay times.

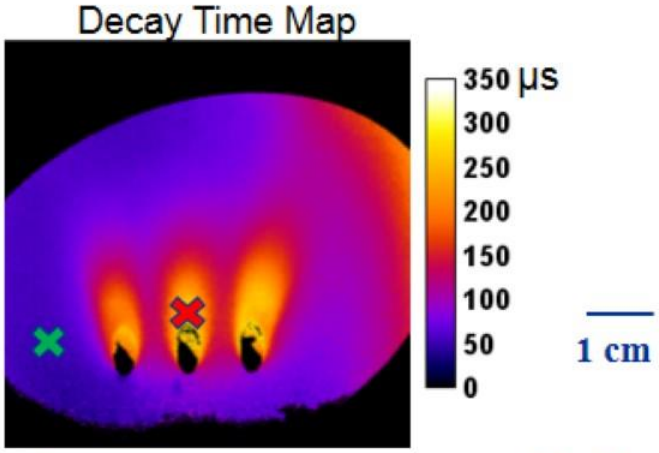


  - Step 3: Preform pre-fit filtering.
    - Insufficient intensity, decay too fast or too slow

2D Temperature Maps from Luminescence Lifetime Imaging

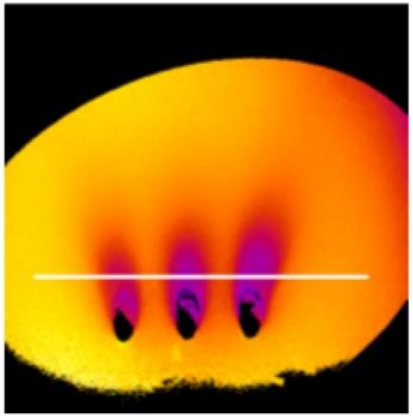
- Step 4: Fit luminescence decay curve at each pixel to produce decay time map. Dyanamic fitting window spans region between 60% and 10% of initial intensity. (Matlab routine).

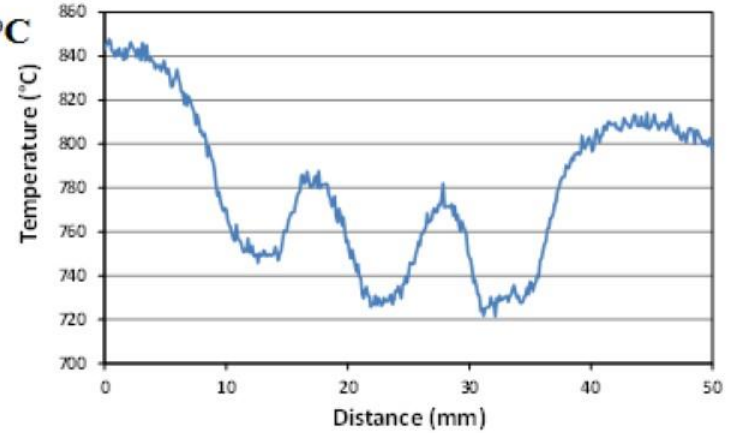


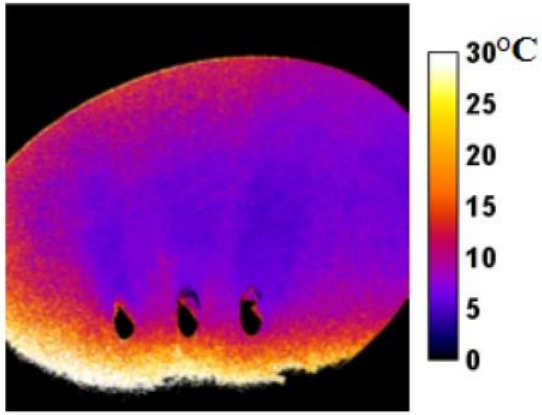


- Step 5: Use calibration data to convert decay time map to temperature map (Matlab routine).

Find T that gives know τ where $\tau = \tau_{2E}^{R} \dfrac{1+3e^{-\Delta E/kT}}{1+\alpha e^{-\Delta E/kT}+\beta e^{-(\Delta Eq+\Delta E)/kT}}$



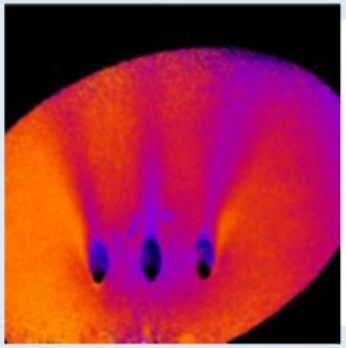




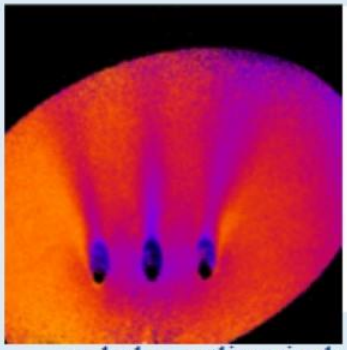
Effect of Luminous Flame Bursts

Decay time temperature maps

95% confidence interval

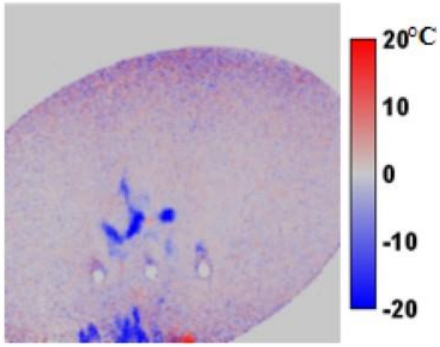


includes outlier pixels



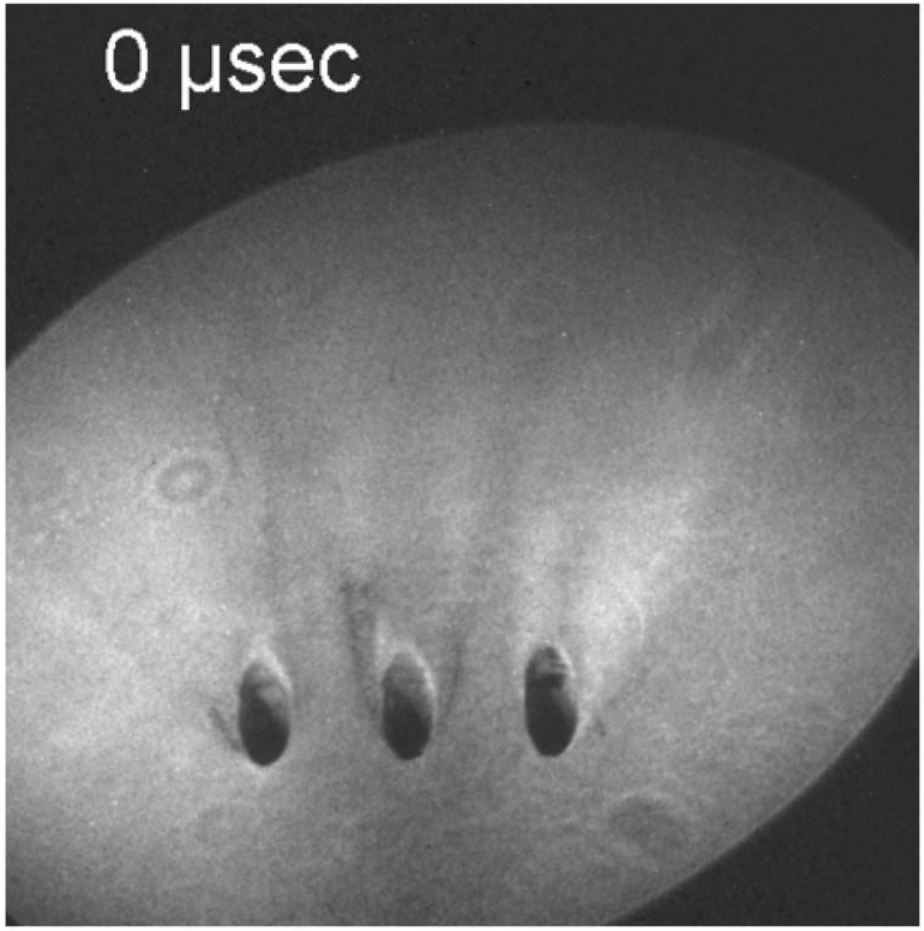
excludes outlier pixels

$T_{included} - T_{excluded}$



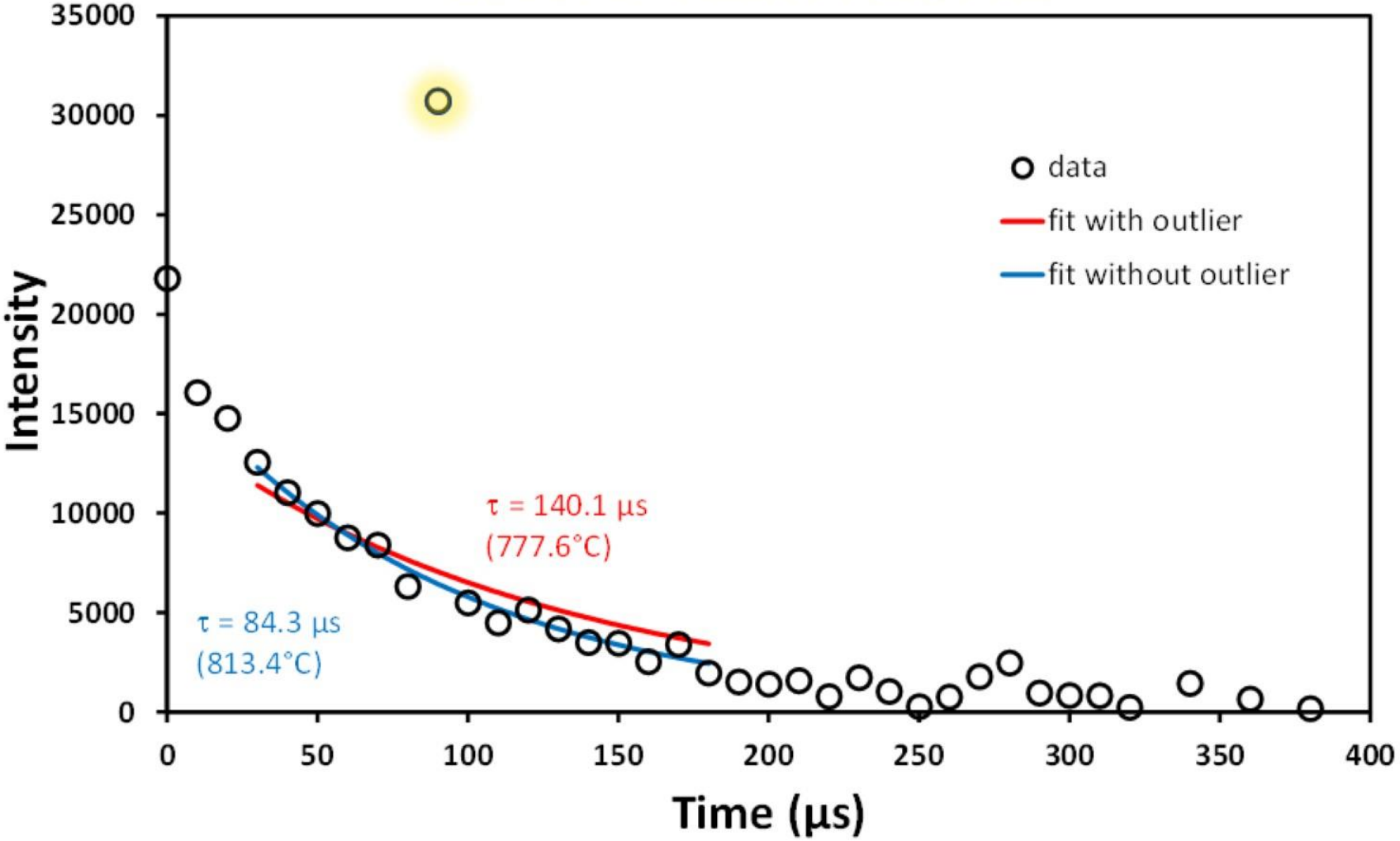
Luminous flame streaks produce local temperature errors ~20°C too low.

Image Stack



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 Δt 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

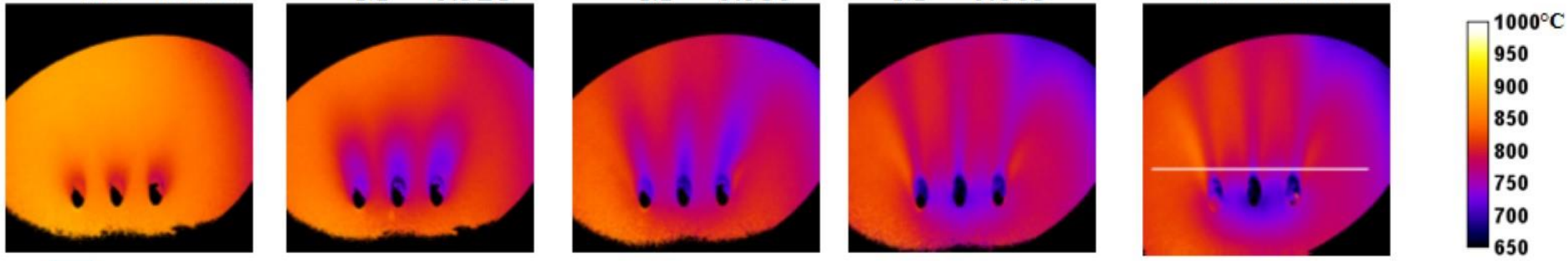
- Examine changes in cooling effectiveness as a function of:
  - Mainstream hot gas temperatures: 1390, 1604, and 1722°C
  - Blowing ratio: M' = 0 to 1.1

Burner Rig 2D Temperature Maps

$T_{mainstream} = 1390°C$

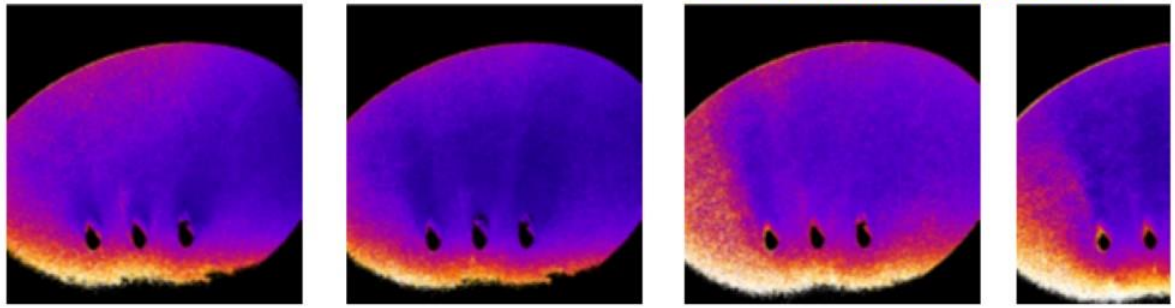
Decay time temperature maps

M' = 0.134 | M' = 0.321 | M' = 0.535 | M' = 0.803 | M' = 0.936

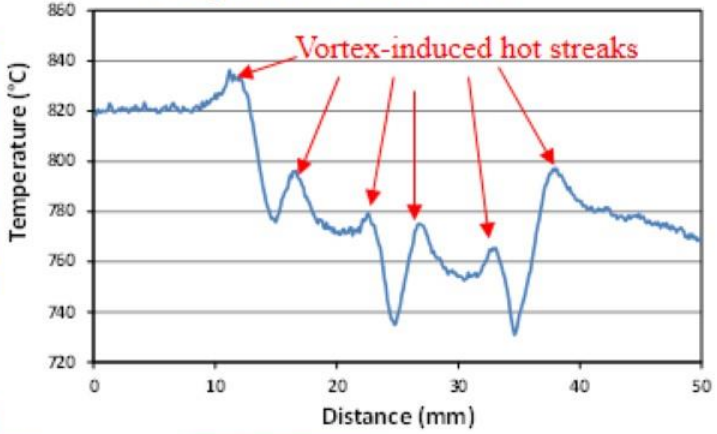


1 cm

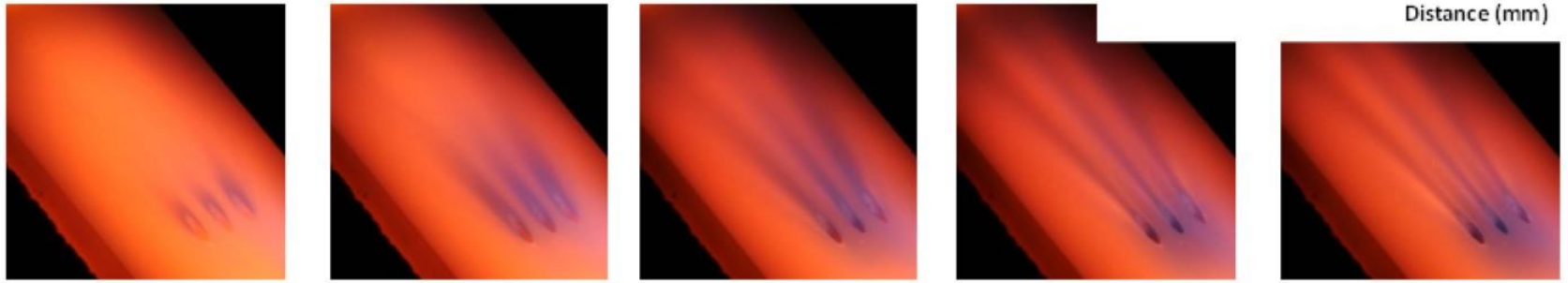
95% confidence interval



Temperature Line Scan



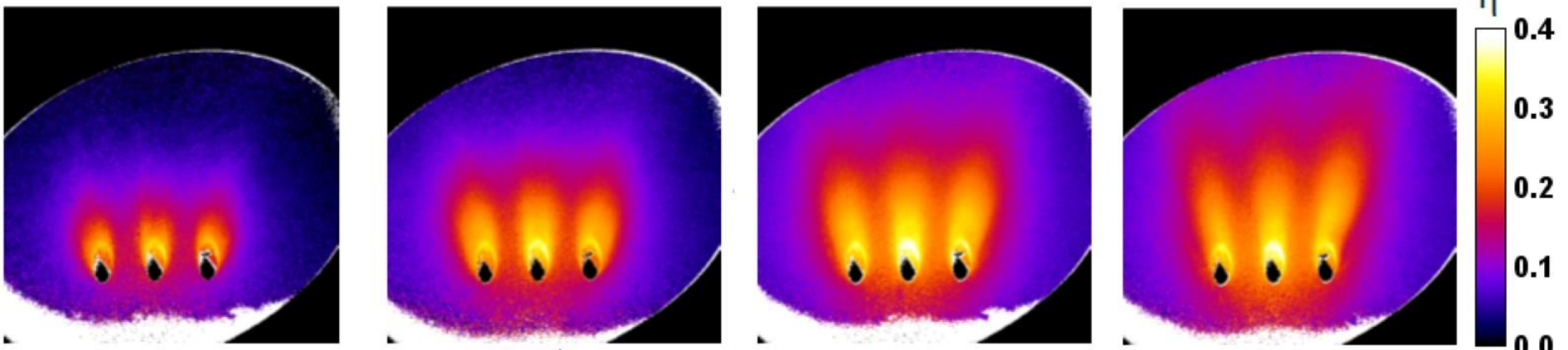
photos



Burner Rig 2D Cooling Effectiveness Maps

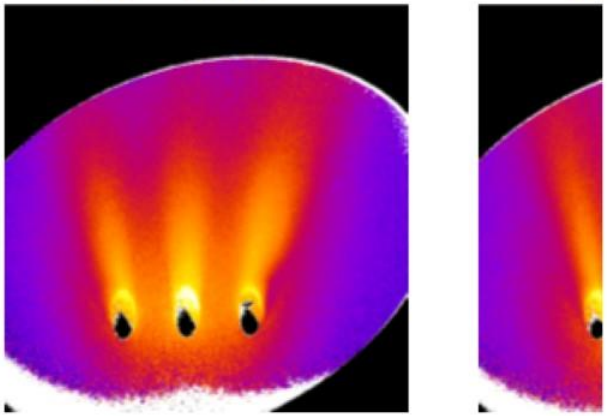
$T_{mainstream} = 1390°C$

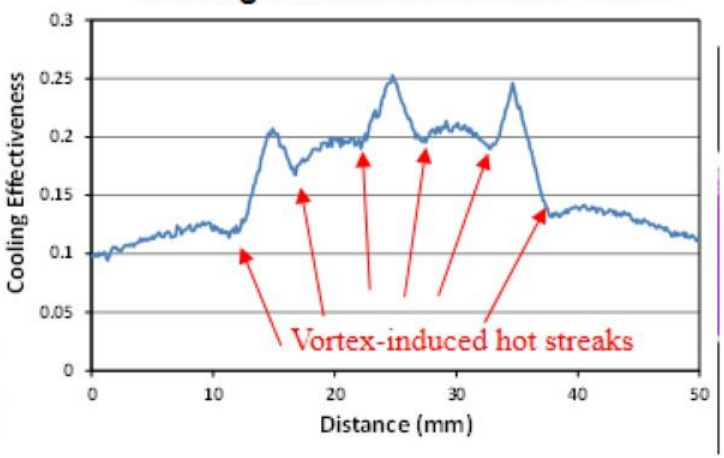
M' = 0.134 M' = 0.214 M' = 0.321 M' = 0.428



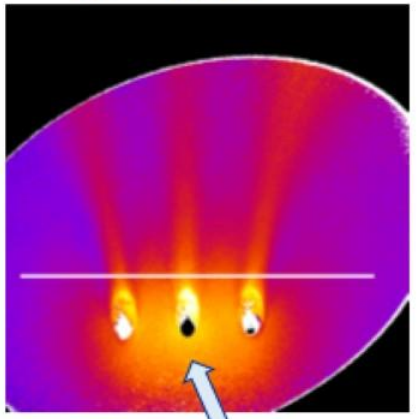
Initially increasing air jet film cooling effectiveness

M' = 0.535 M





M' = 0.936



1 cm

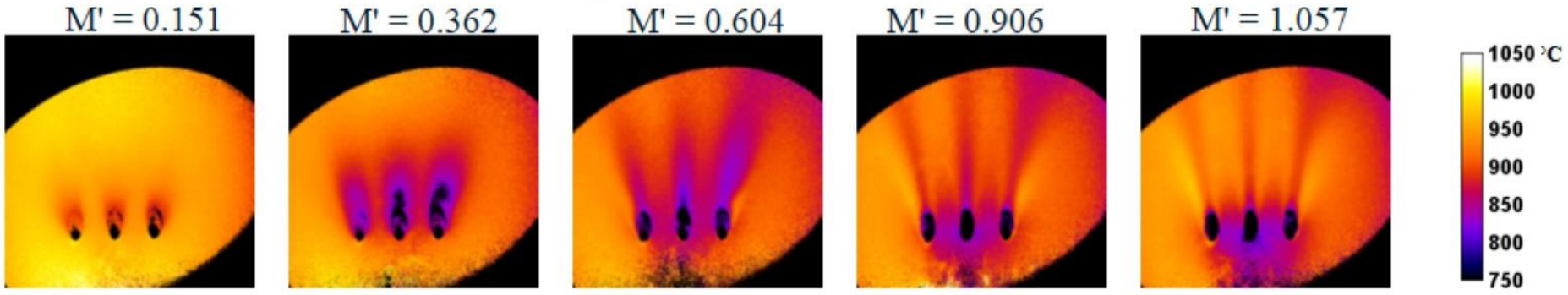
Rapidly increasing through-hole convection cooling effectiveness
Diminishing air film cooling effectiveness with air jet lift-off
Appearance of vortex-induced hot streaks

Upstream through-hole convective cooling

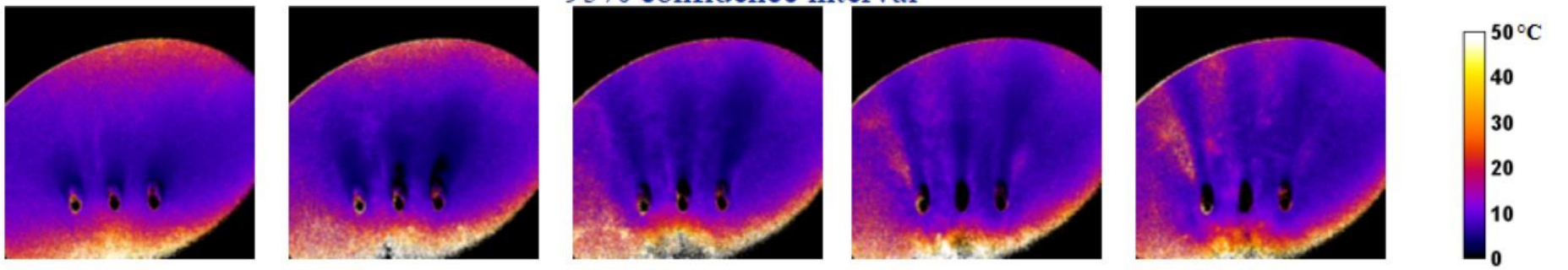
Burner Rig 2D Temperature Maps

$T_{mainstream}$ = 1604°C

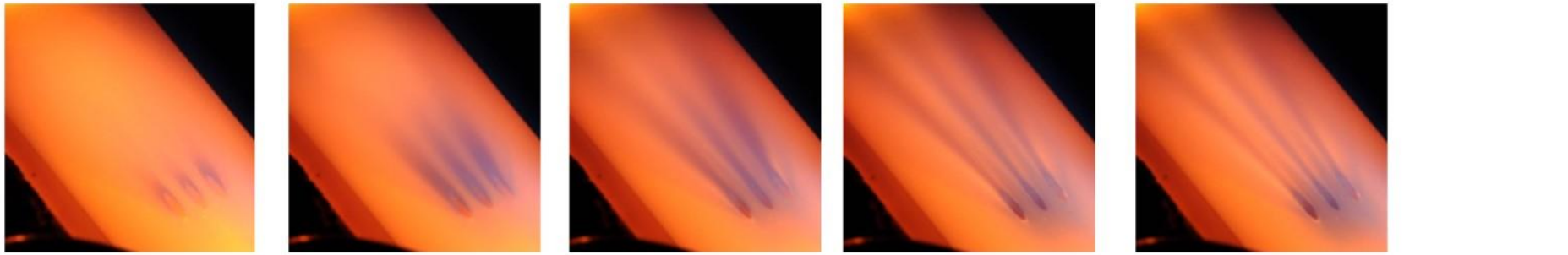
Decay time temperature maps



95% confidence interval

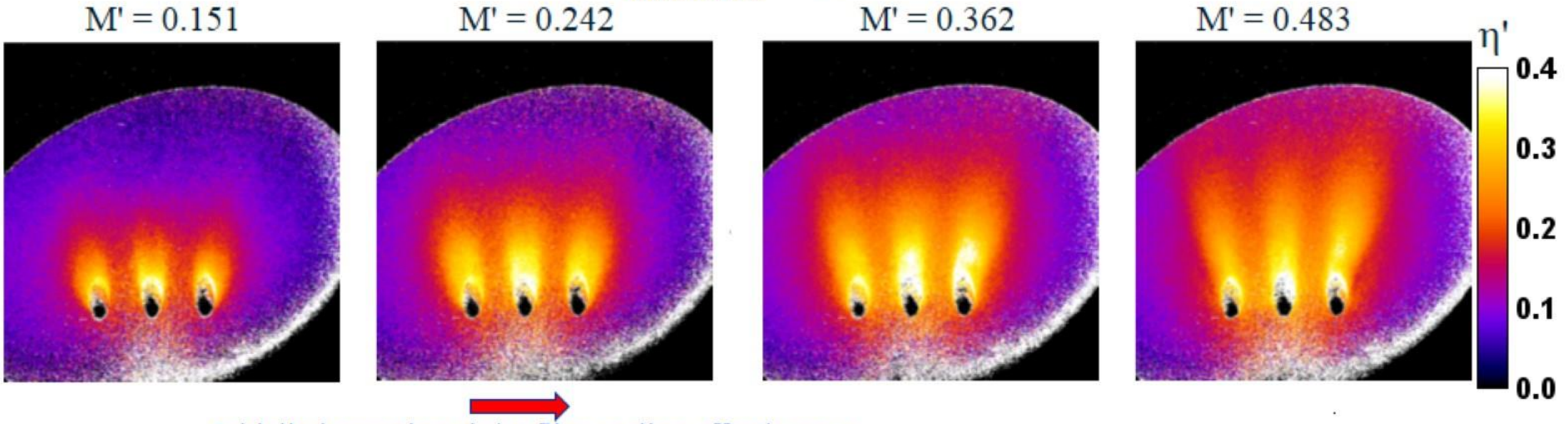


photos

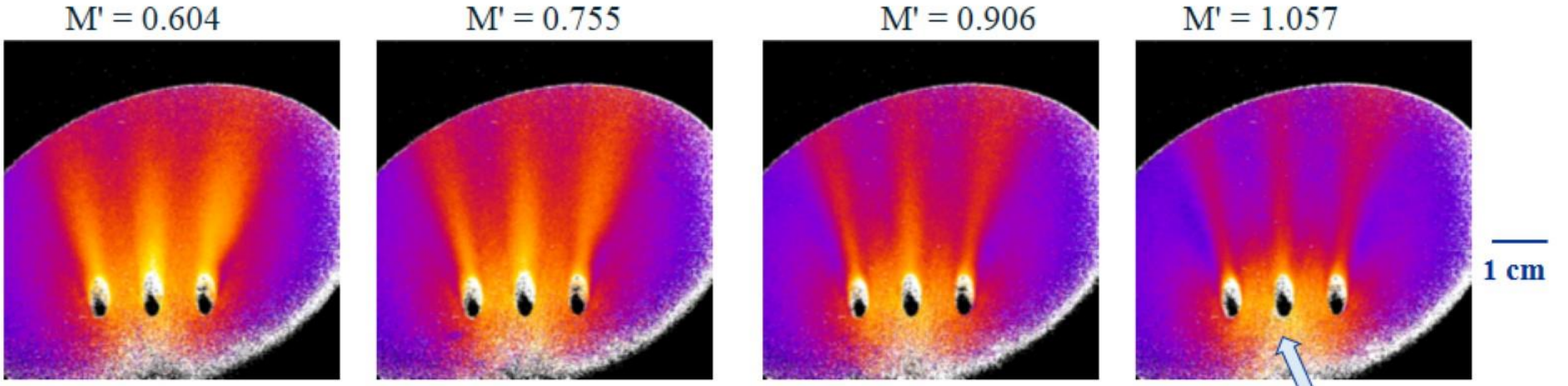


Burner Rig 2D Cooling Effectiveness Maps

$T_{mainstream} = 1604°C$



Initially increasing air jet film cooling effectiveness

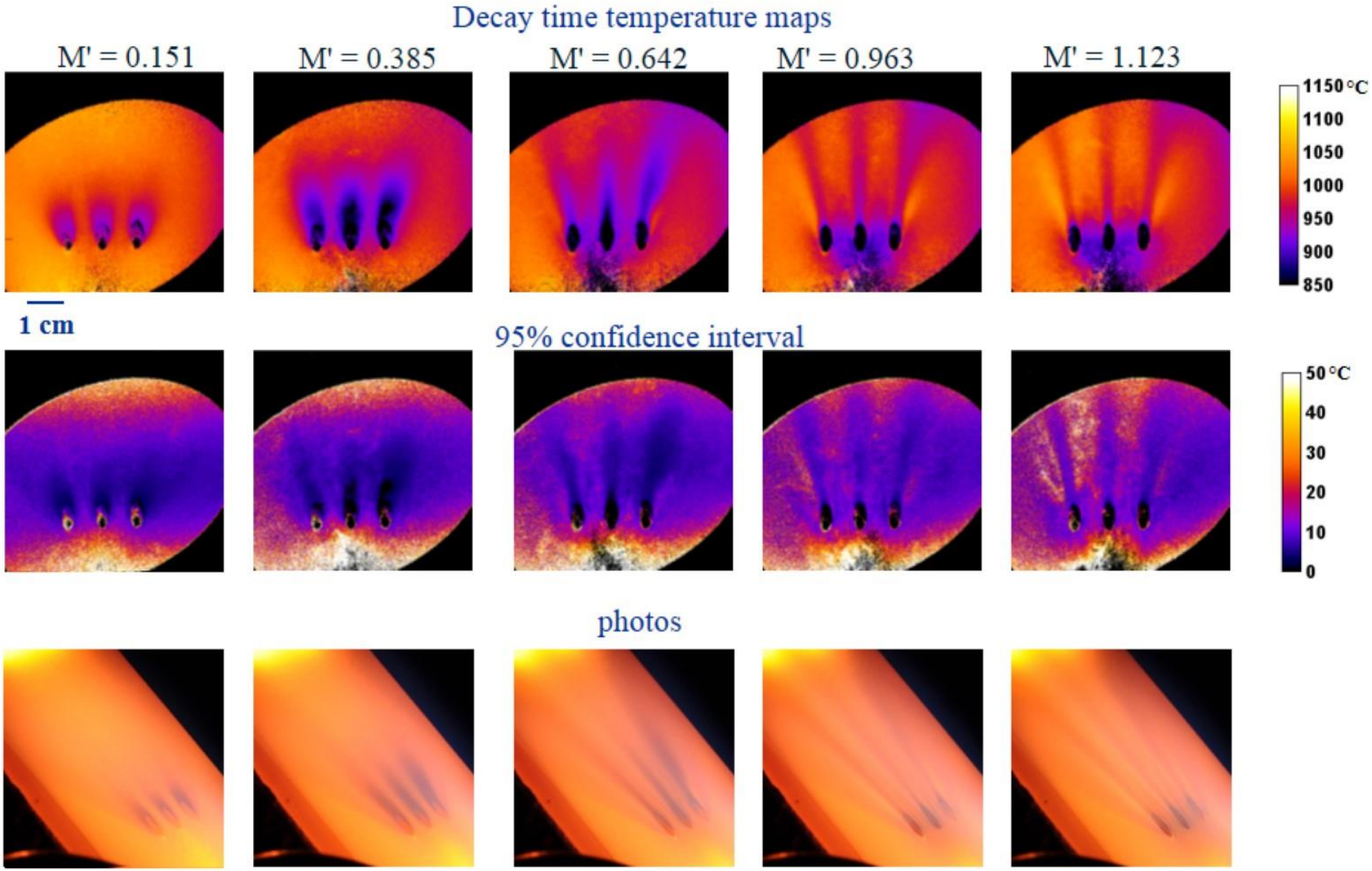


Rapidly increasing through-hole convection cooling effectiveness
Diminishing air film cooling effectiveness with air jet lift-off
Appearance of vortex-induced hot streaks

Upstream through-hole convective cooling

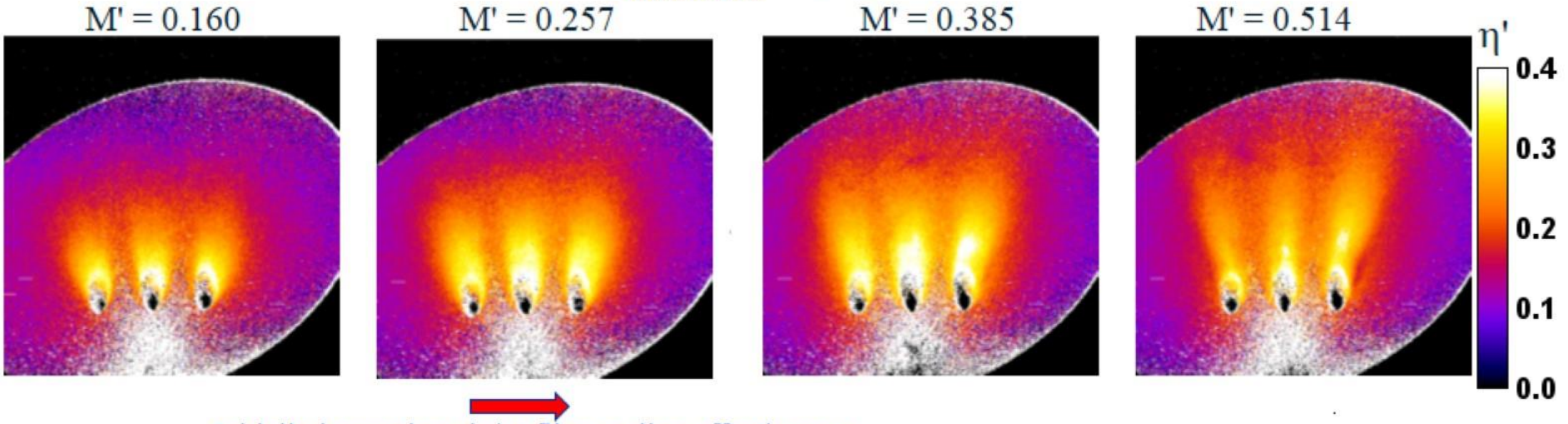
Burner Rig 2D Temperature Maps

$T_{mainstream} = 1722°C$

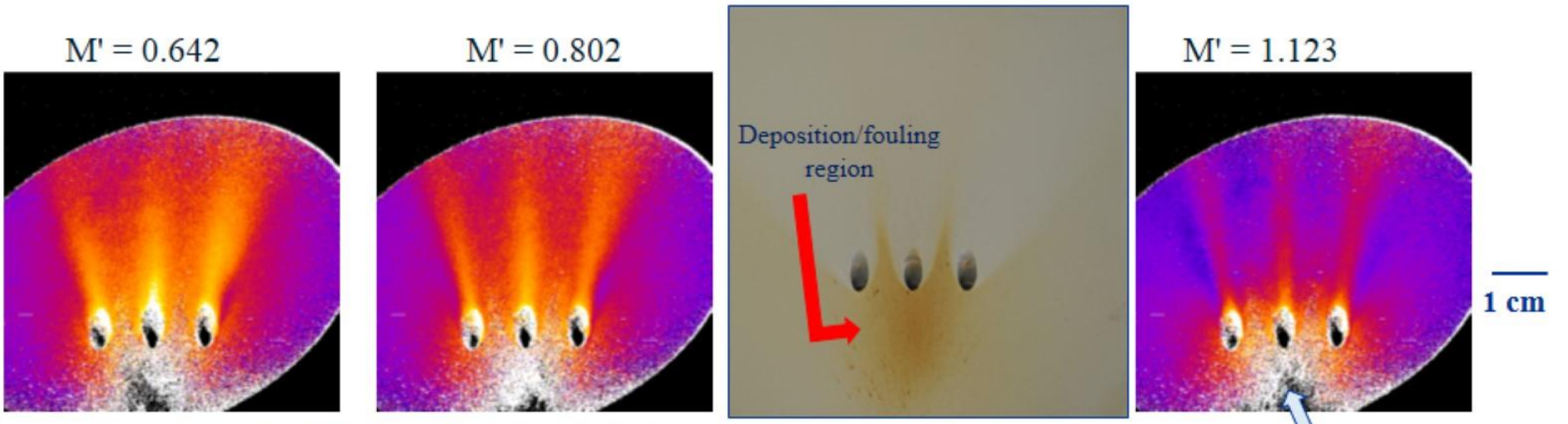


Burner Rig 2D Cooling Effectiveness Maps

$T_{mainstream} = 1722°C$



Initially increasing air jet film cooling effectiveness

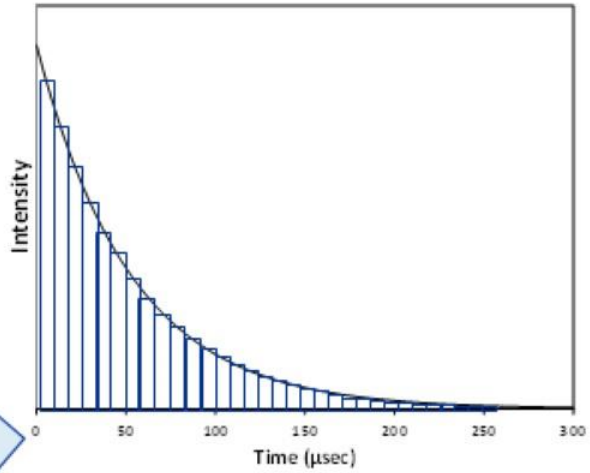


Rapidly increasing through-hole convection cooling effectiveness
Diminishing air film cooling effectiveness with air jet lift-off
Appearance of vortex-induced hot streaks

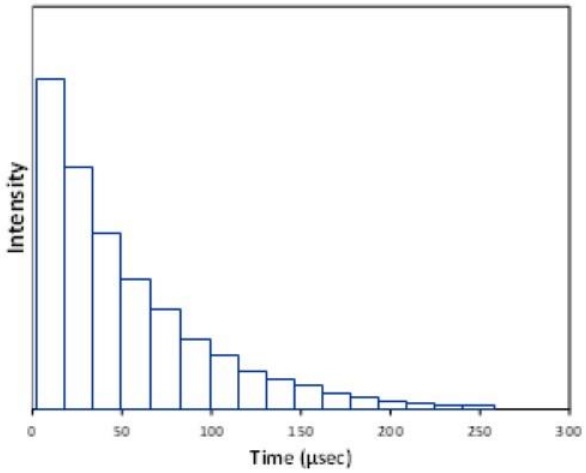
Signal attenuation due to flame deposit

How Many Frames Do We Really Need?

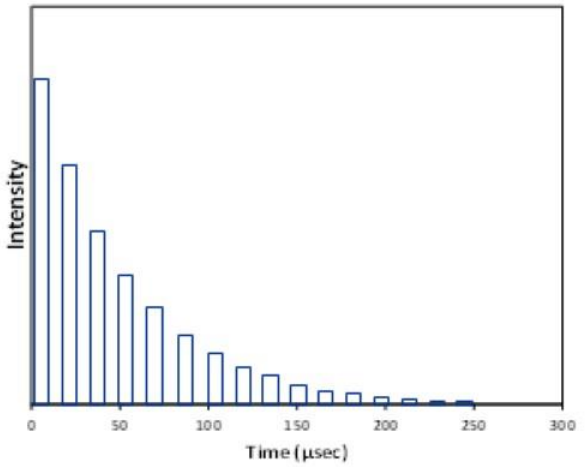
64 frames requires minimum 3 s, up to minutes at highest temperatures



2x binning



2x decimation



*n*x binning = *n*x faster acquisition

*n*x decimation = *n*x faster acquisition

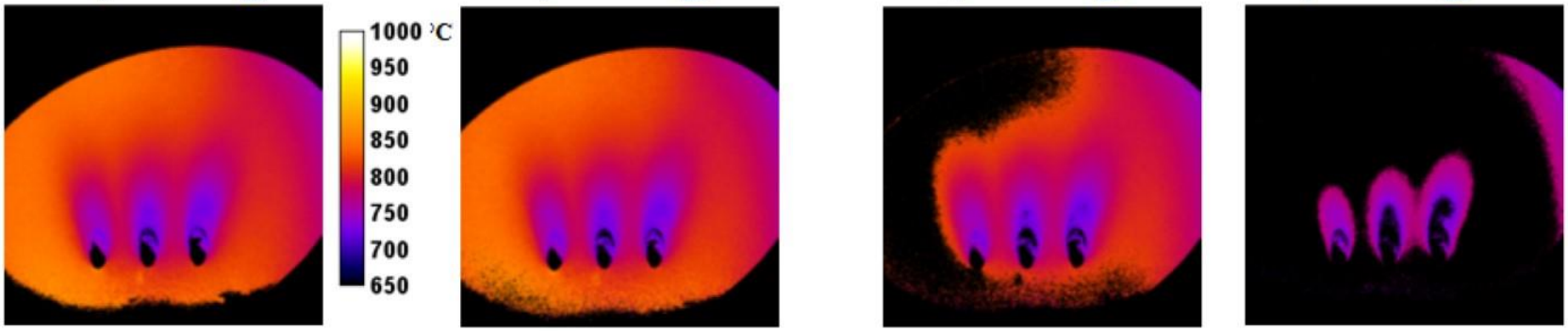
Burner Rig 2D Temperature Maps
Effect of Binning

$T_{mainstream}$ = 1390°C

M' = 0.321

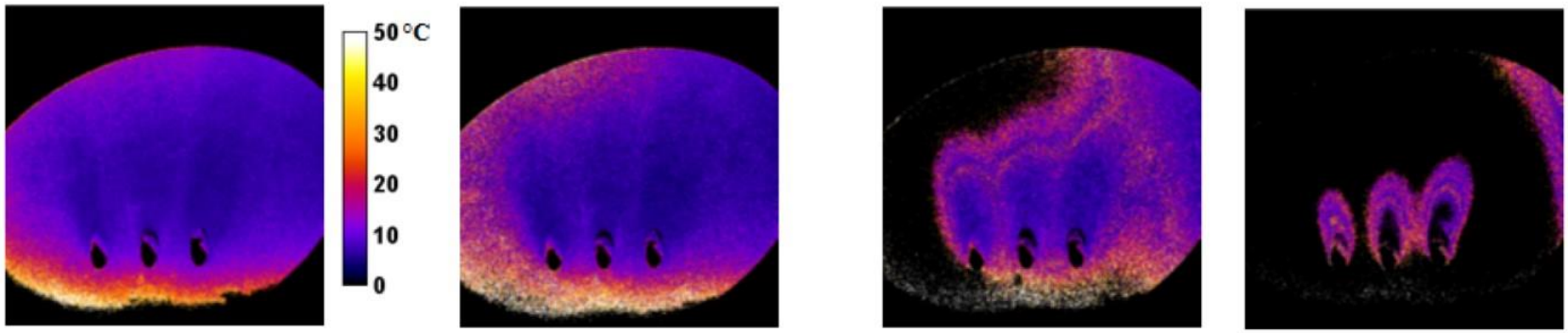
64 frames (no binning) | 32 frames (2x binning) | 16 frames (4x binning) | 8 frames (8x binning)

Decay time temperature maps



1 cm

95% confidence interval

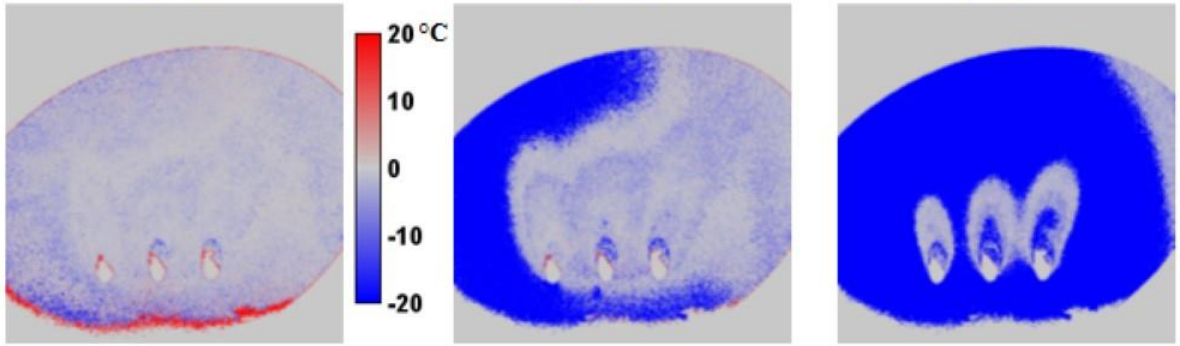


$\Delta T = T_{binned} - T_{unbinned}$

*n*x binning = *n*x faster acquisition

Binning effects
- Limits temperature range
- Modest decrease in precision
- Produces very little bias

T_{32}-T_{64} | T_{16}-T_{64} | T_{8}-T_{64}



Burner Rig 2D Temperature Maps
Effect of Binning

$T_{mainstream}$ = 1390°C

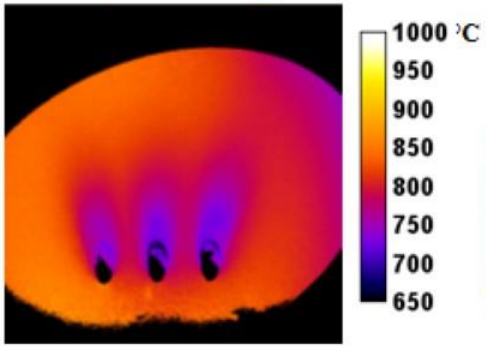
M' = 0.321

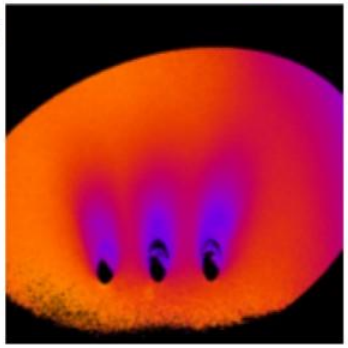
64 frames (no binning)

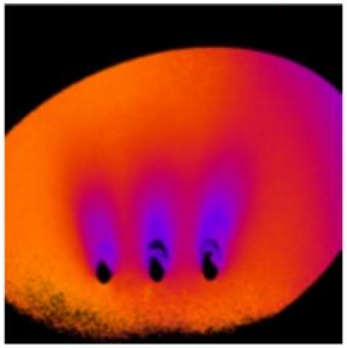
32 frames (2x binning)

32 frames (2x decimation)

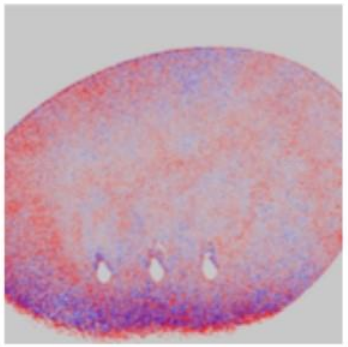
Decay time temperature maps

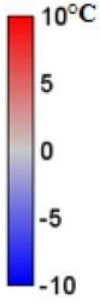






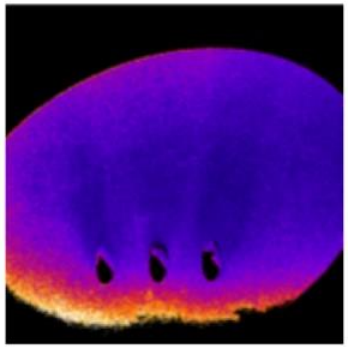
2x decimated minus 2x binned

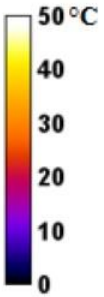


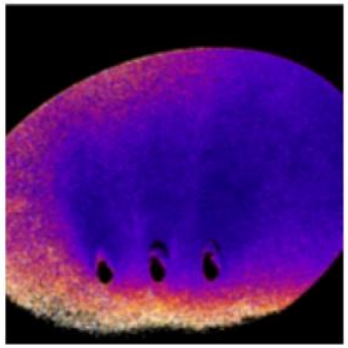


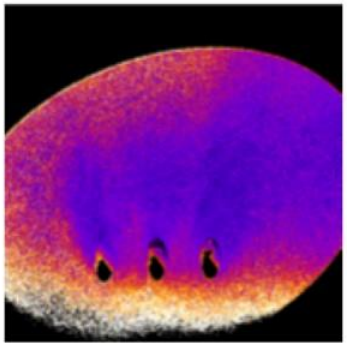
1 cm

95% confidence interval



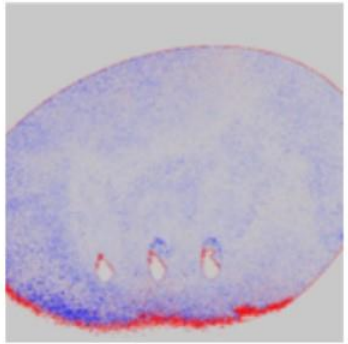


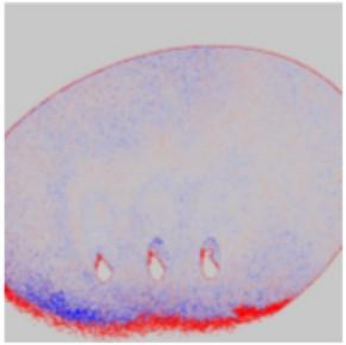


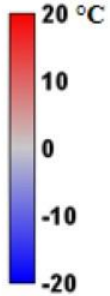


T_{16}-T_{64}

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

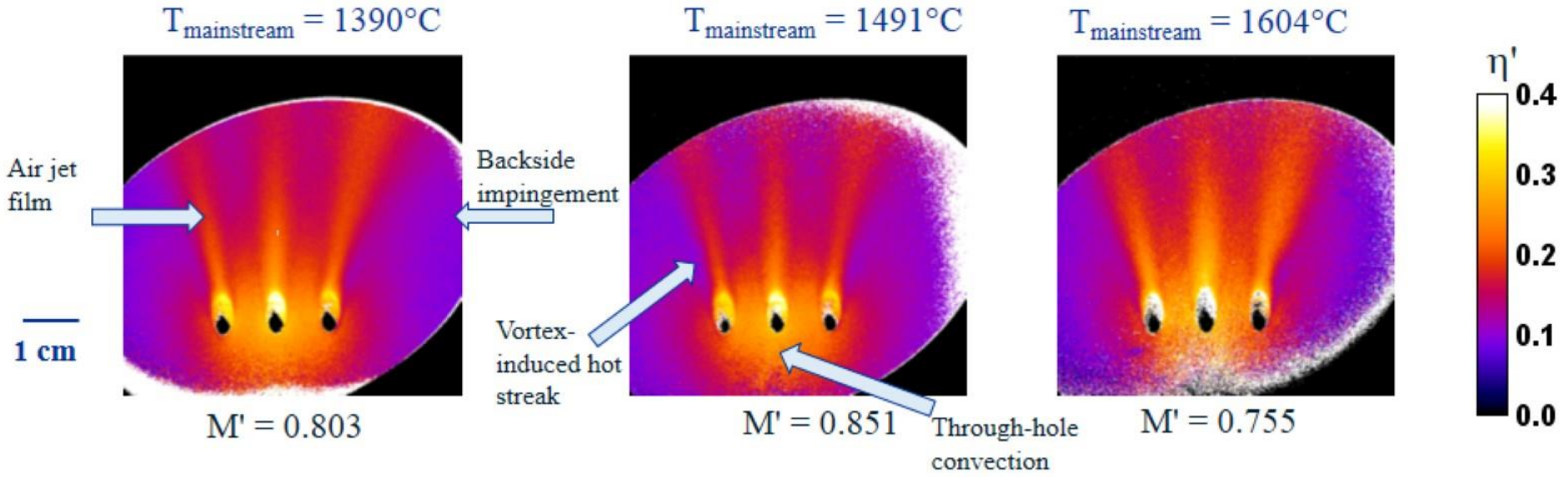






*n*x binning = *n*x faster acquisition

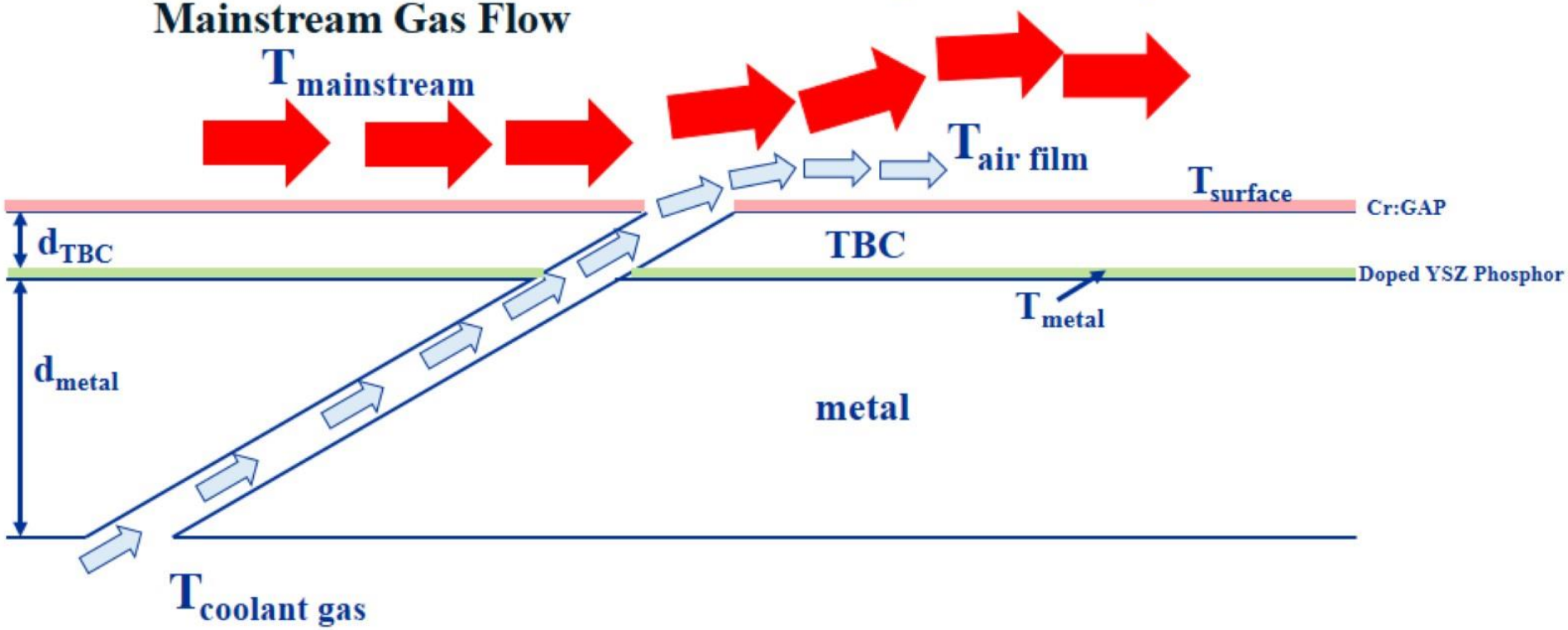
Combined Cooling Effects Summary



- 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



Surface cooling effectiveness from Cr:GAP layer:

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

Metal cooling effectiveness from doped YSZ layer:

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

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