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

Jeffrey I. Eldridge, Vikram Shyam, Adam C. Wroblewski, and Dongming Zhu
NASA Glenn Research Center, Cleveland, OH

Michael D. Cuy
Vantage Partners, Cleveland, OH

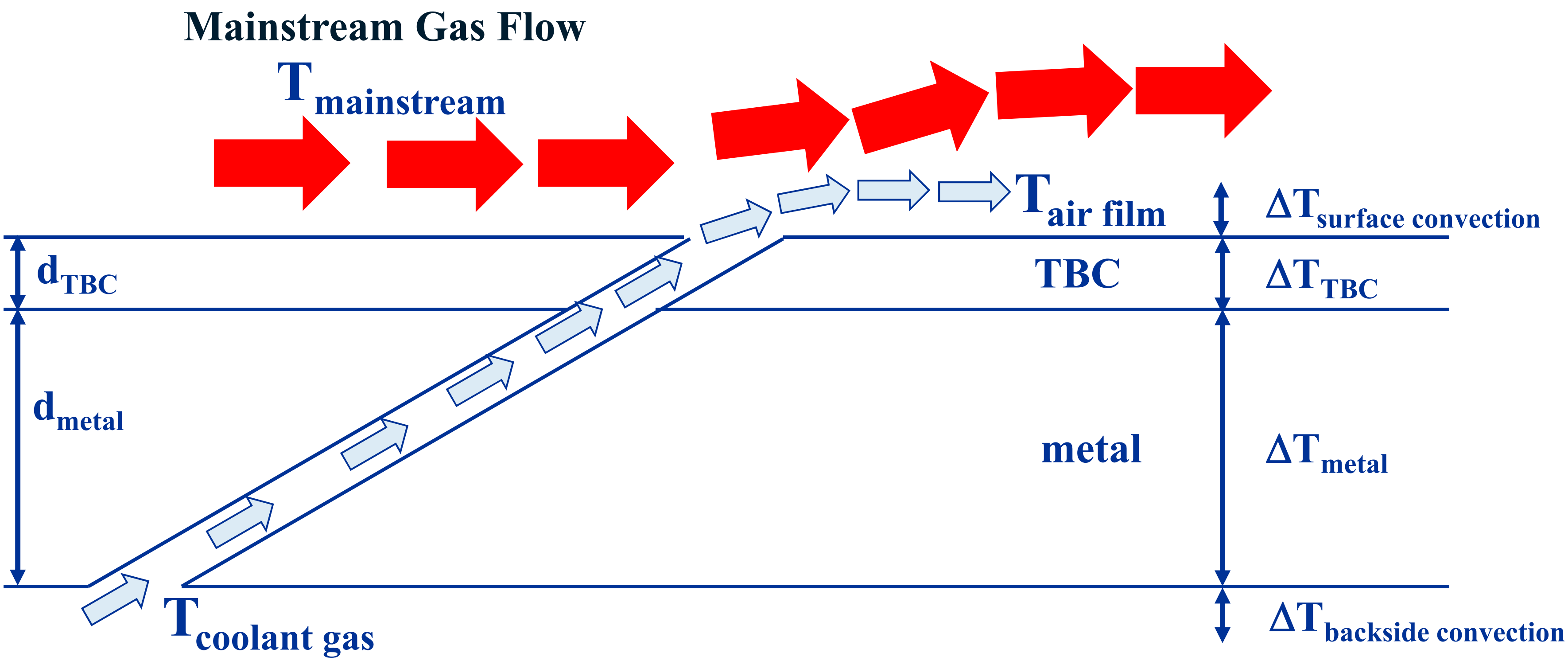
Douglas E. Wolfe
Penn State University, University Park, PA

Aviation 2016
Washington, D.C.
June 13-17, 2016

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)

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

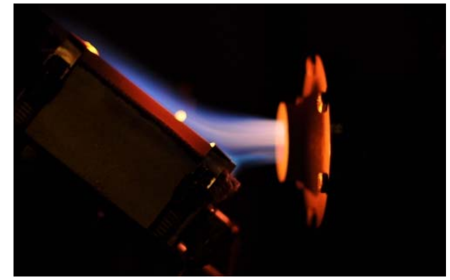
- Air film cooling greatly reduces effective h_{conv} and therefore greatly reduces Φ_{TBC}
- Air film cooling greatly reduces q and therefore ΔT_{TBC}

- 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

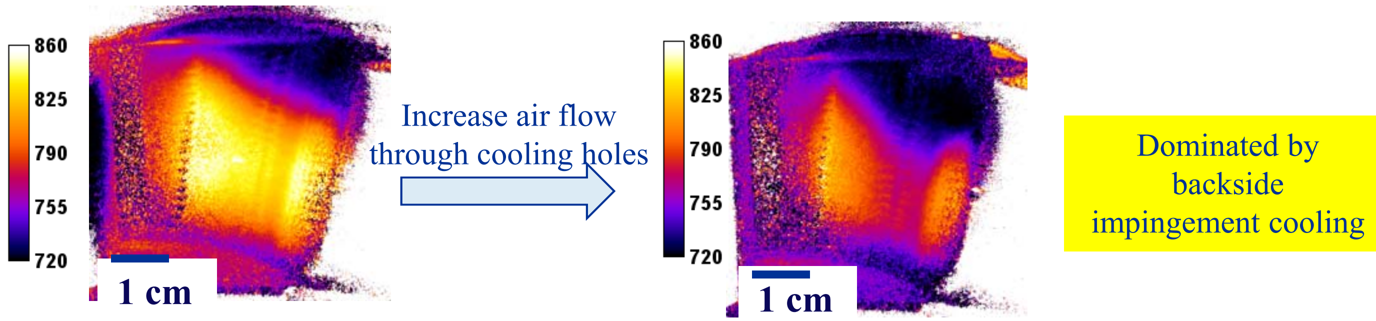
- Experimentally map effectiveness of air film cooling on TBC-coated surfaces.
- Examine changes in cooling effectiveness as a function of:
  - Mainstream hot gas temperature
  - Blowing ratio (cooling air flow)
- Examine interplay between air film cooling, backside impingement cooling, and through-hole convective cooling for TBC-coated substrate.

Approach



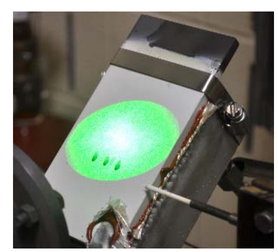
- Perform measurements in NASA GRC Mach 0.3 burner rig.
  - Vary flame temperature and blowing ratio.
- Perform measurements on TBC-coated superalloy plate with scaled up simple cooling hole geometry.
  - Initial testing of actual vane component did not produce effective air film cooling.

Cr:GAP coated vane with cooling air supply tubing

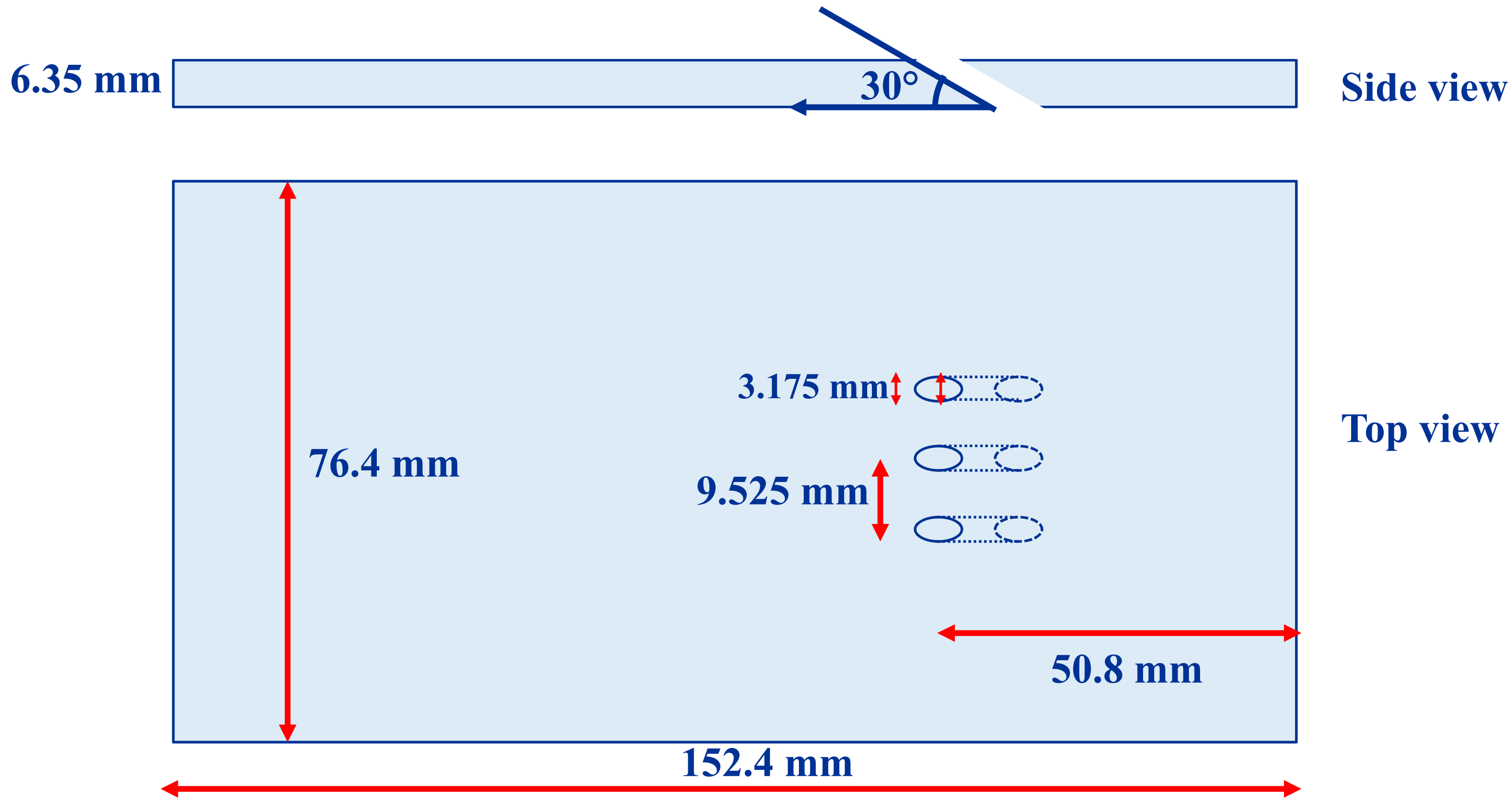


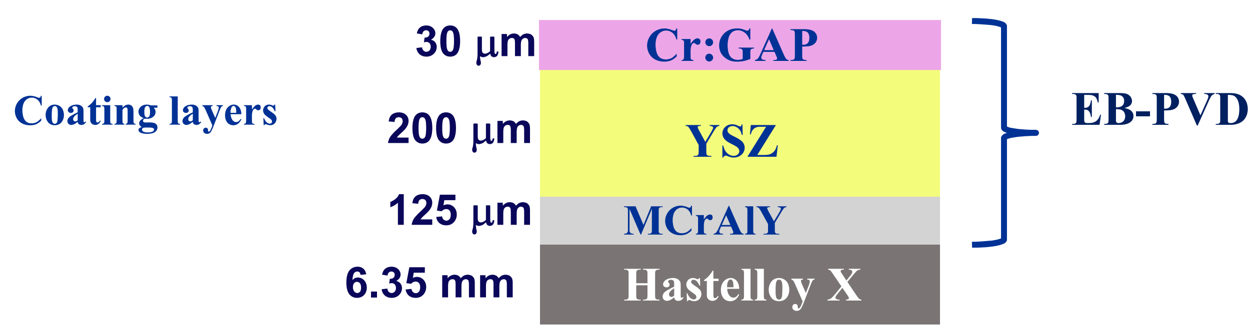
Surface temperature maps of stator vane doublet in Mach 0.3 burner rig

- 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. ✗



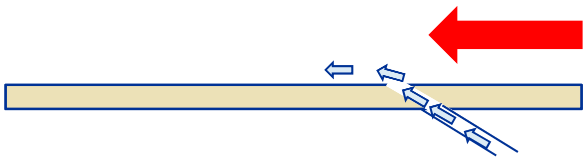
Cooling Hole Plate Geometry





Cooling Effectiveness Measurements

Conventional Air Film Cooling Effectiveness Test

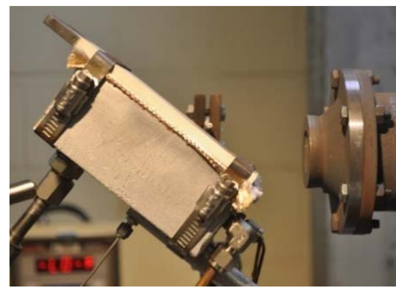


- Uniform mainstream flow (velocity & temperature)
- Typical surface temperatures: < 100°C
- Measure adiabatic air film cooling effectiveness, η

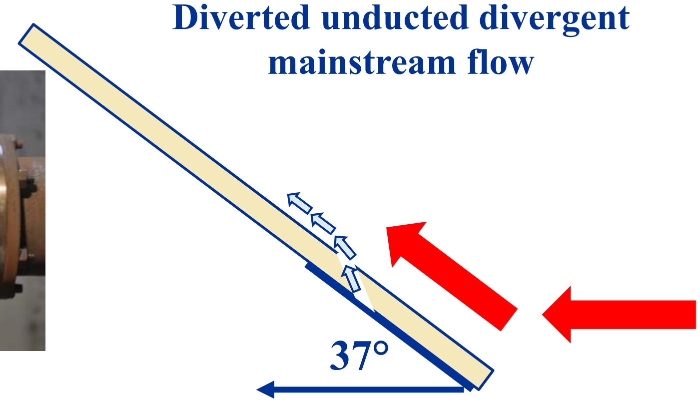
$$\eta = \frac{T_{mainstream} - T^{adiabatic}_{surface}}{T_{mainstream} - T_{coolant\ exit}}$$

- 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'

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

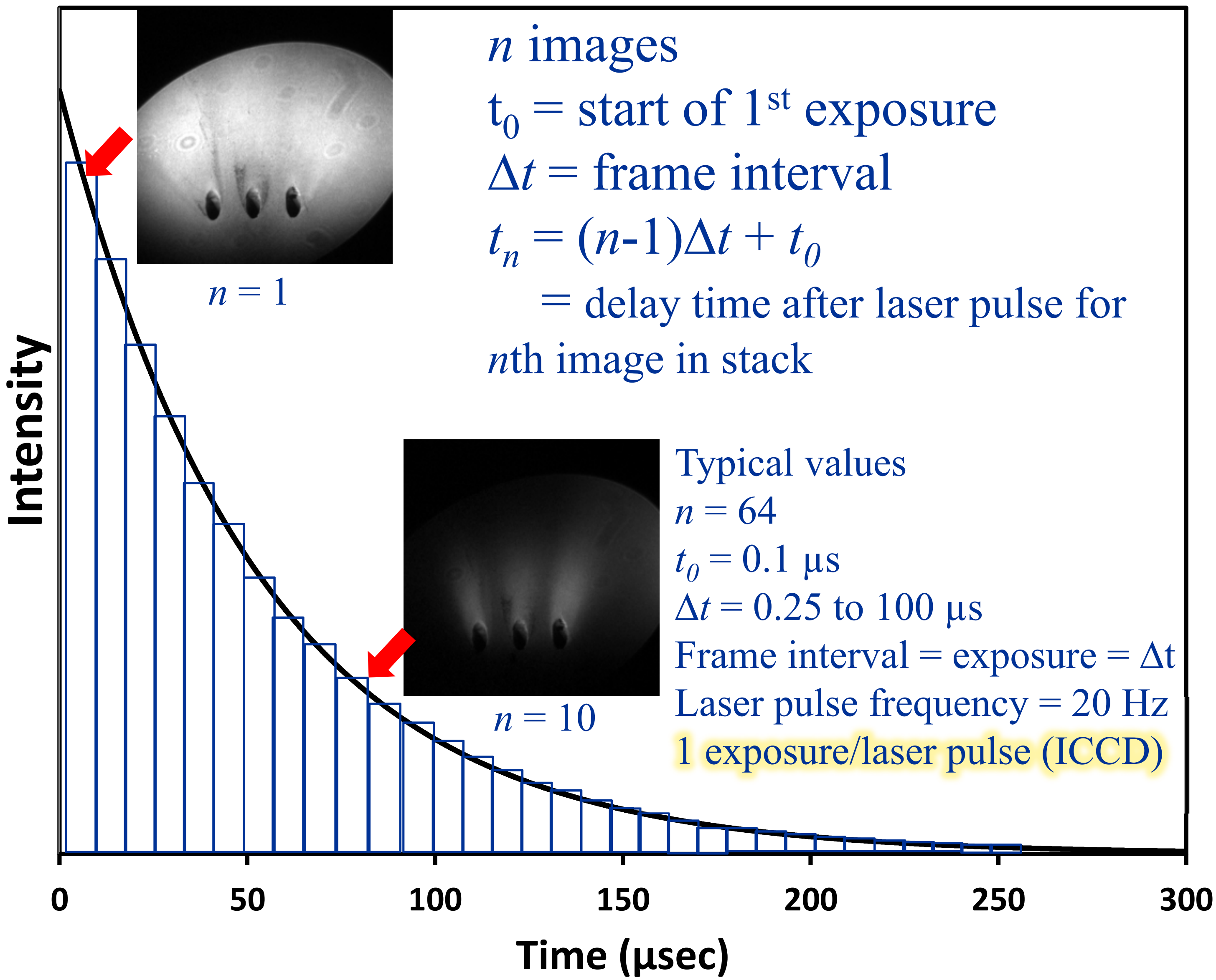
- η' is a nonfundamental but realistic characterization of combined surface cooling effects
- Measure η' as a function of M

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

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

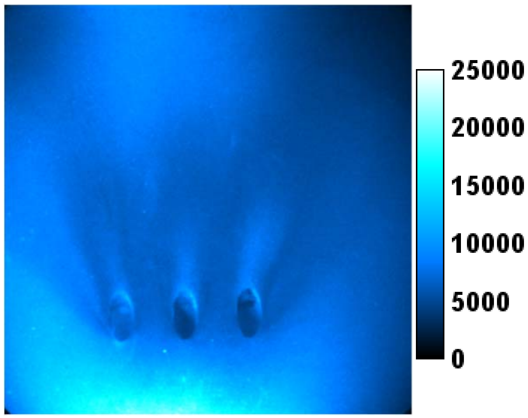
Luminescence Lifetime Image Stack



2D Temperature Maps from Luminescence Lifetime Imaging

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

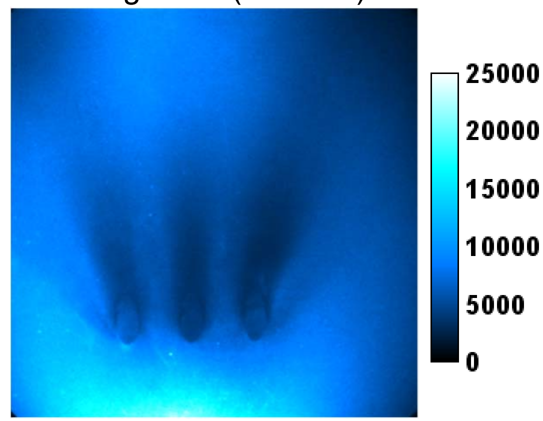
Luminescence before background subtraction



10 μs exposure 300 μs after laser pulse

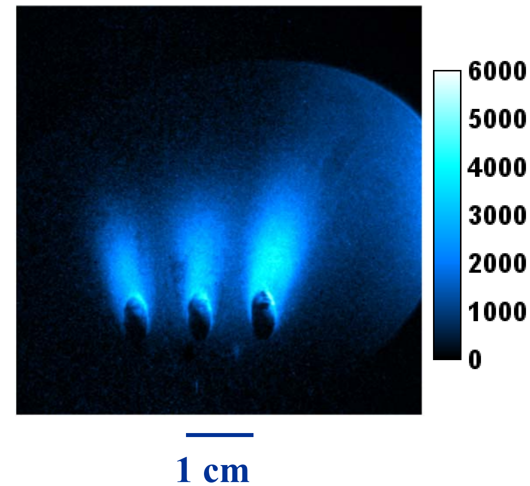
\-

Background (no laser)

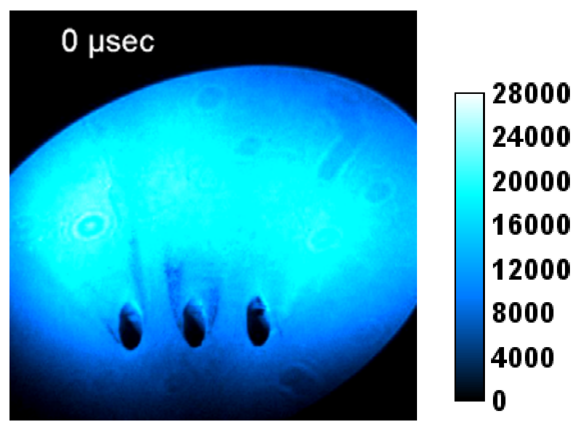


=

Luminescence after background subtraction



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

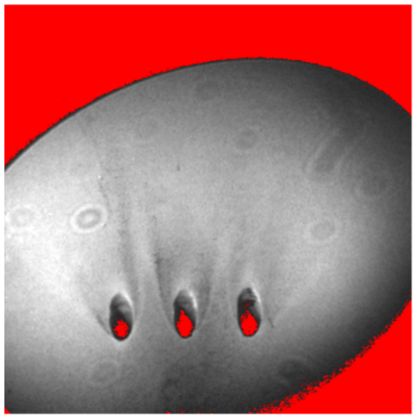


  - Step 3: Preform pre-fit filtering.

Pre-Fit Data Filtering

Criteria for removing pixels unsuitable for temperature determination

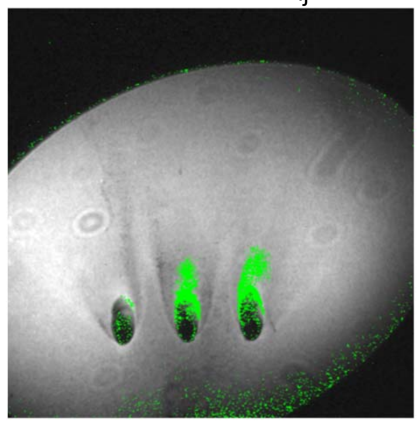
Minimum absolute threshold
I_{ij}(frame 1) < 2200



1 cm

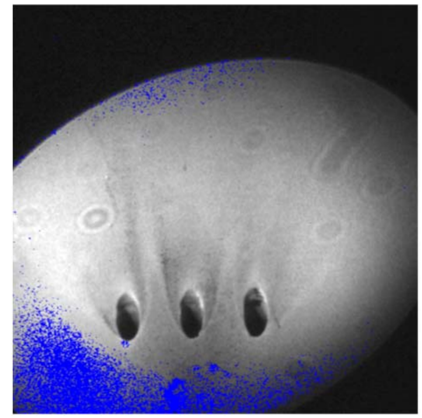
Insufficient signal

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



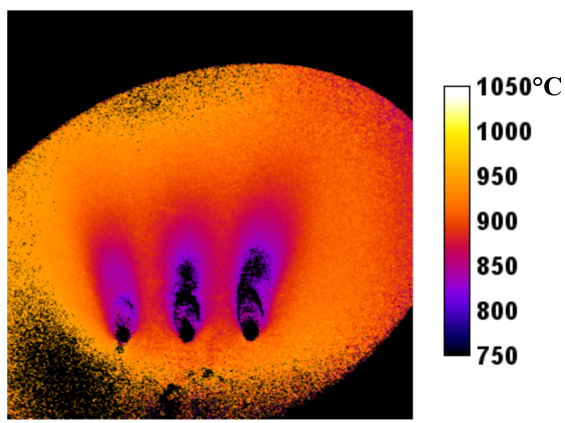
Too cold: need to extend to longer delay times after laser pulse

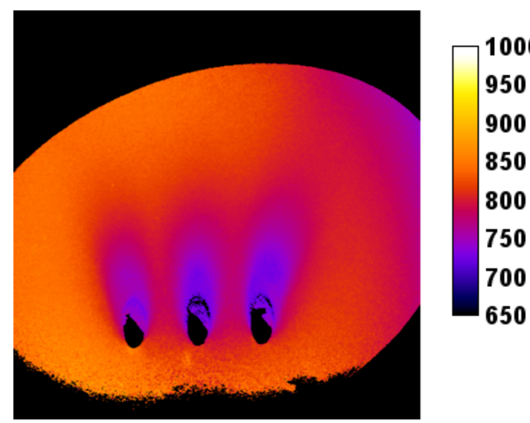
Minimum number of frames in fitting interval
10%*I_{ij}(first frame) < I_{ij}(frame n) < 90%*I_{ij}(first frame)
Number of frames < 6



Too hot: need smaller increments of delay time

Post-fit temperature map



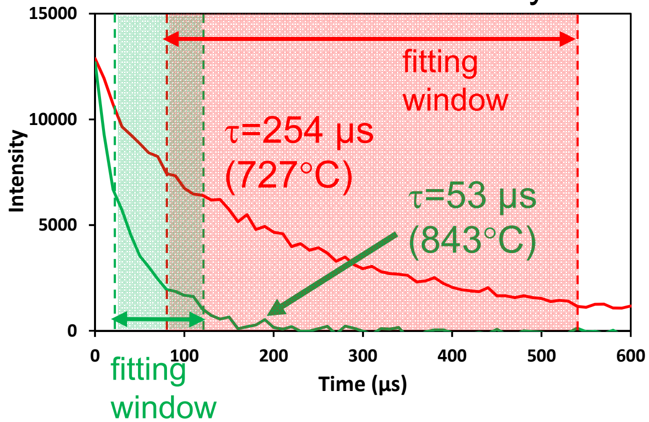


Example of better delay time range & increments

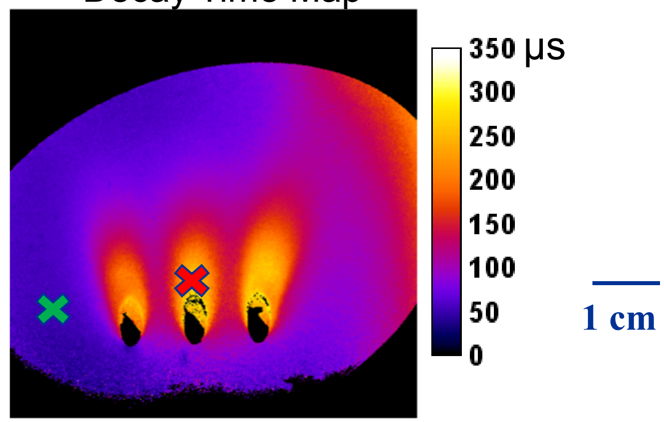
2D Temperature Maps from Luminescence Lifetime Imaging

– 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).

Individual Pixel Decays



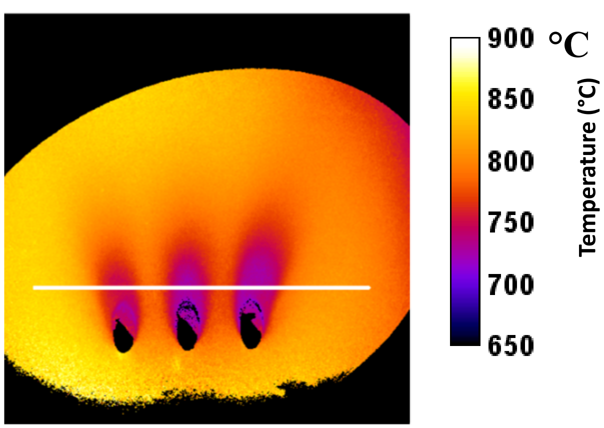
Decay Time Map



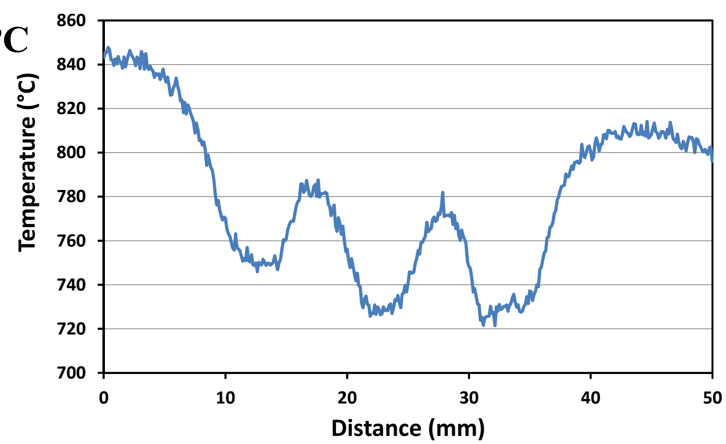
– Step 5: Use calibration data to convert decay time map to temperature map (Matlab routine).

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

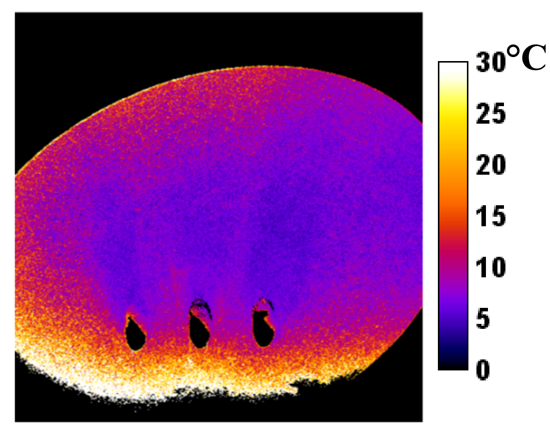
Temperature Map



Temperature Line Scan



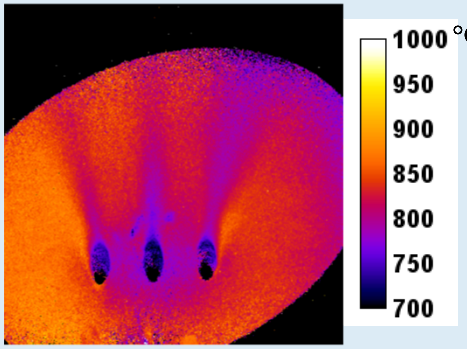
95% Confidence Interval



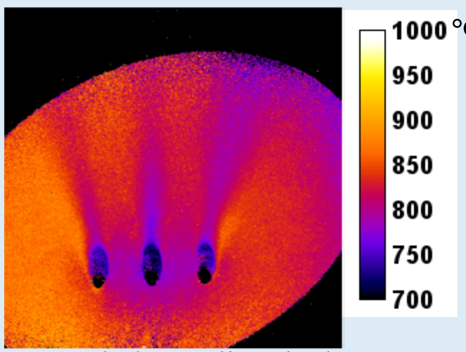
Effect of Luminous Flame Bursts

Decay time temperature maps

95% confidence interval

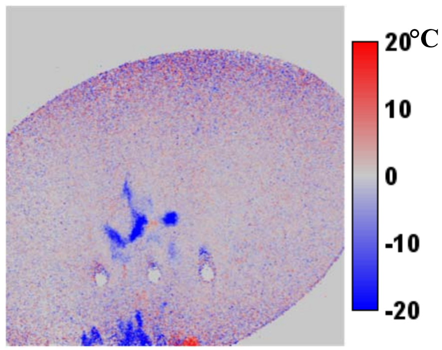


includes outlier pixels



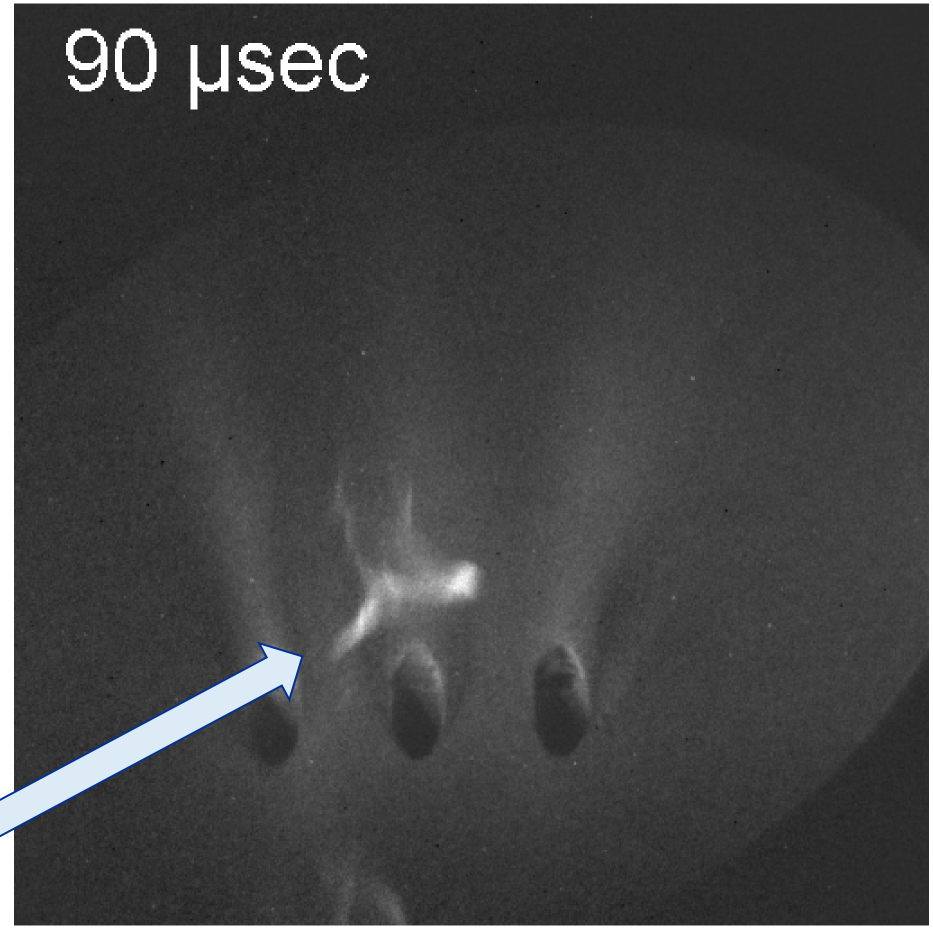
excludes outlier pixels

$T_{included} - T_{excluded}$



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

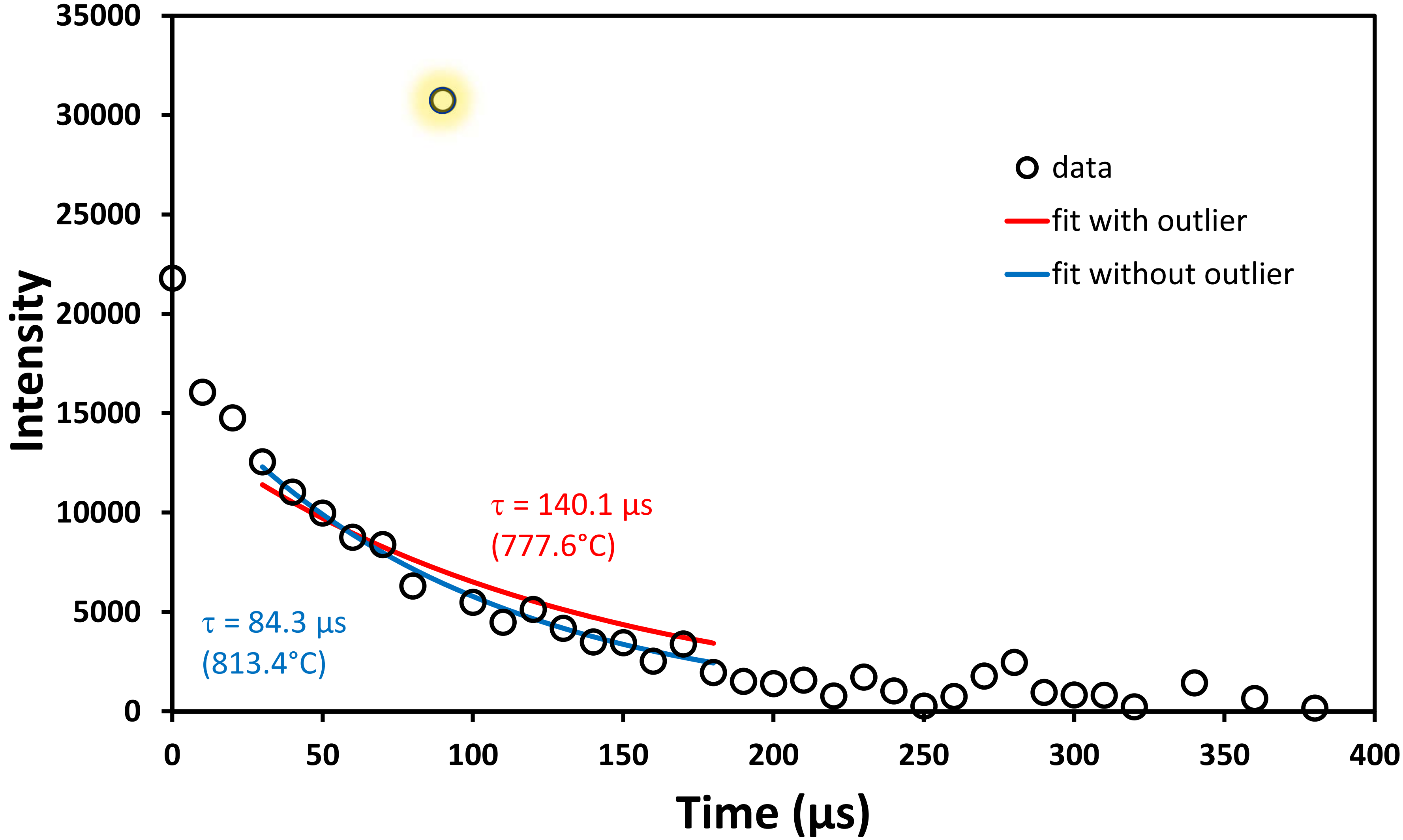
Tenth Image in Stack



Burning particle

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

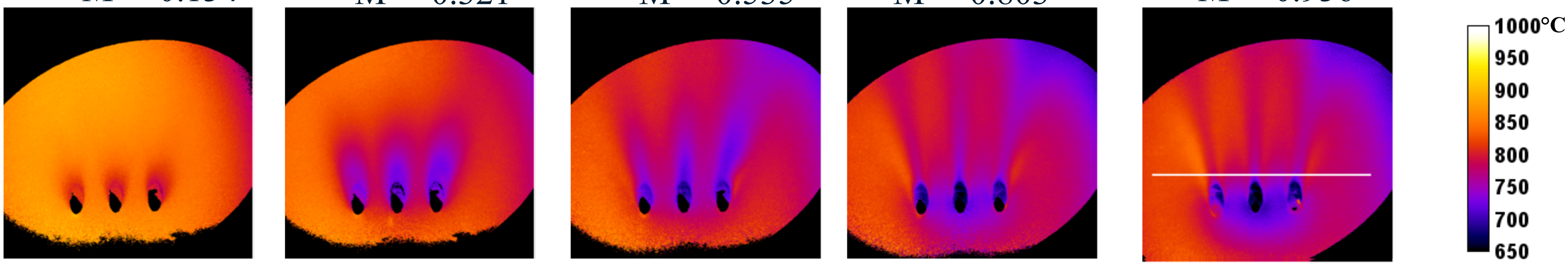
- Examine changes in cooling effectiveness as a function of:
  - Mainstream hot gas temperatures: 1390, 1604, and 1722°C
  - Blowing ratio: M' = 0 to 1.1

Burner Rig 2D Temperature Maps

$T_{mainstream} = 1390°C$

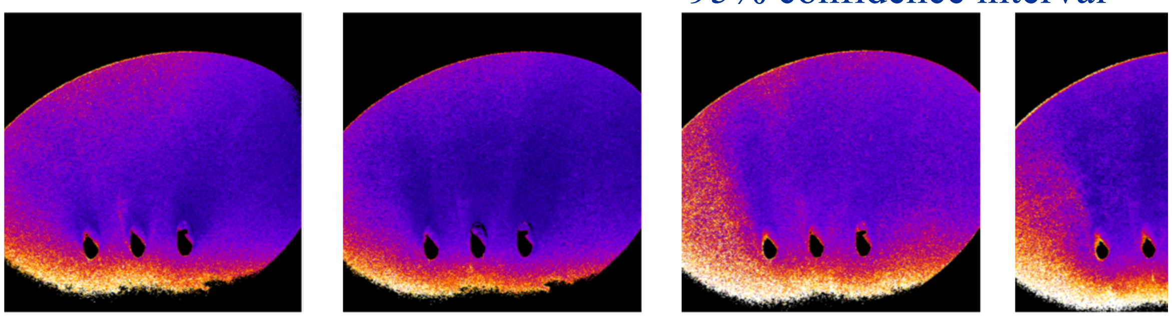
Decay time temperature maps

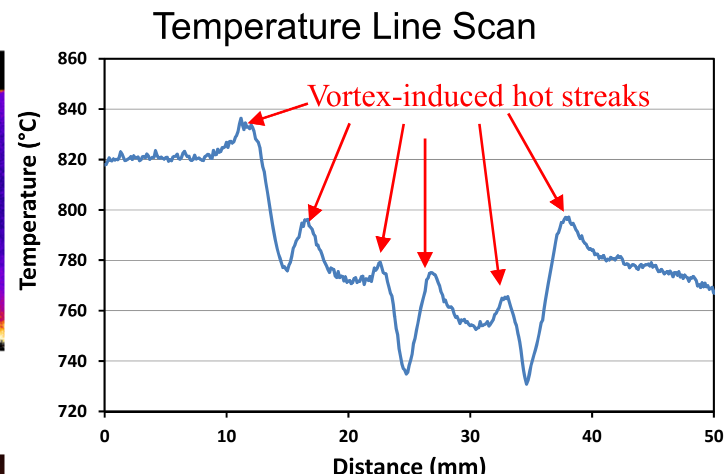
M' = 0.134 M' = 0.321 M' = 0.535 M' = 0.803 M' = 0.936



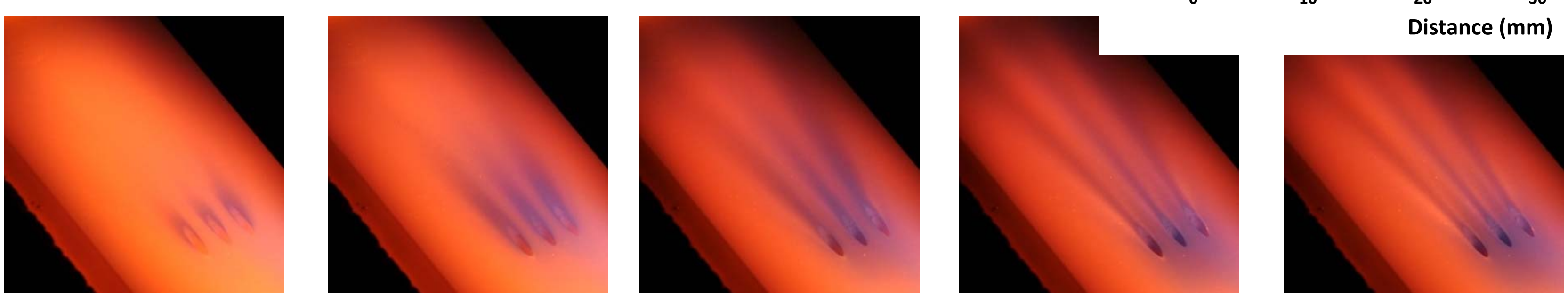
1 cm

95% confidence interval





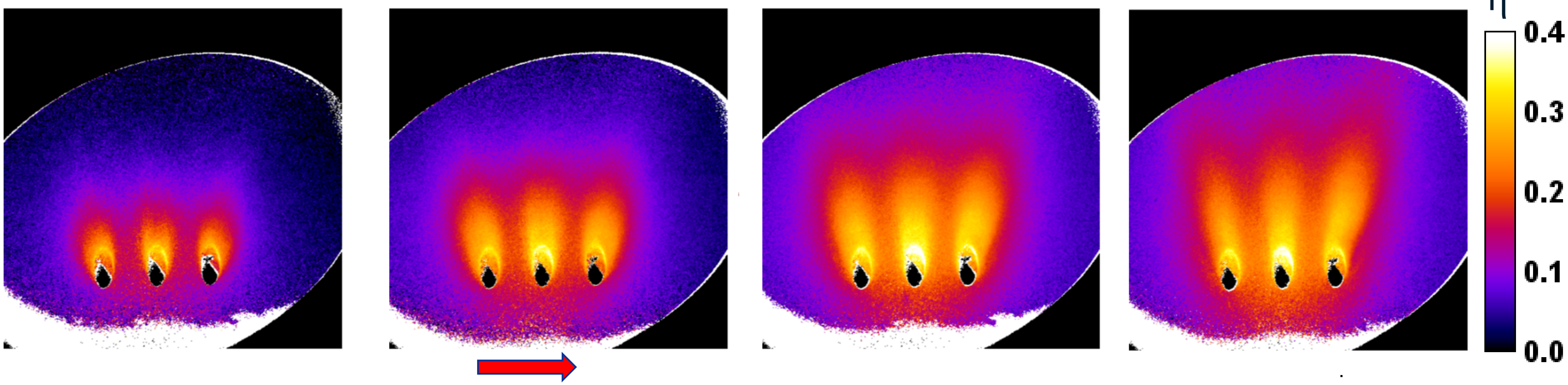
photos



Burner Rig 2D Cooling Effectiveness Maps

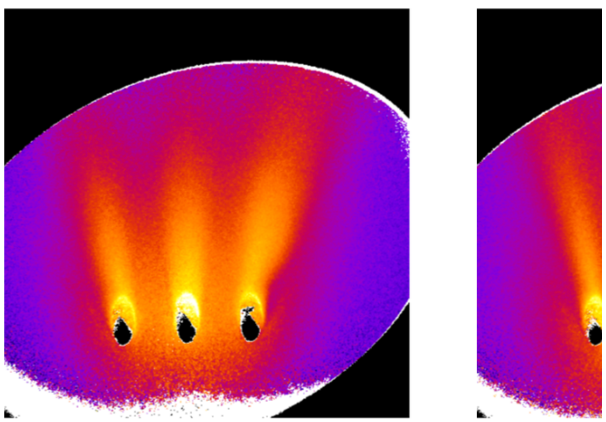
$T_{mainstream} = 1390°C$

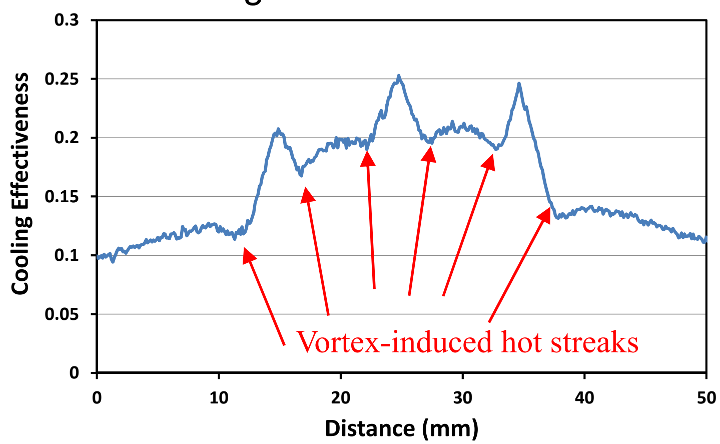
M' = 0.134　M' = 0.214　M' = 0.321　M' = 0.428



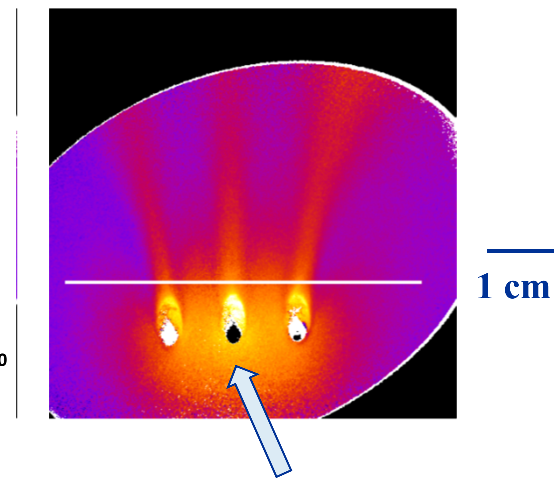
Initially increasing air jet film cooling effectiveness

M' = 0.535　M





M' = 0.936

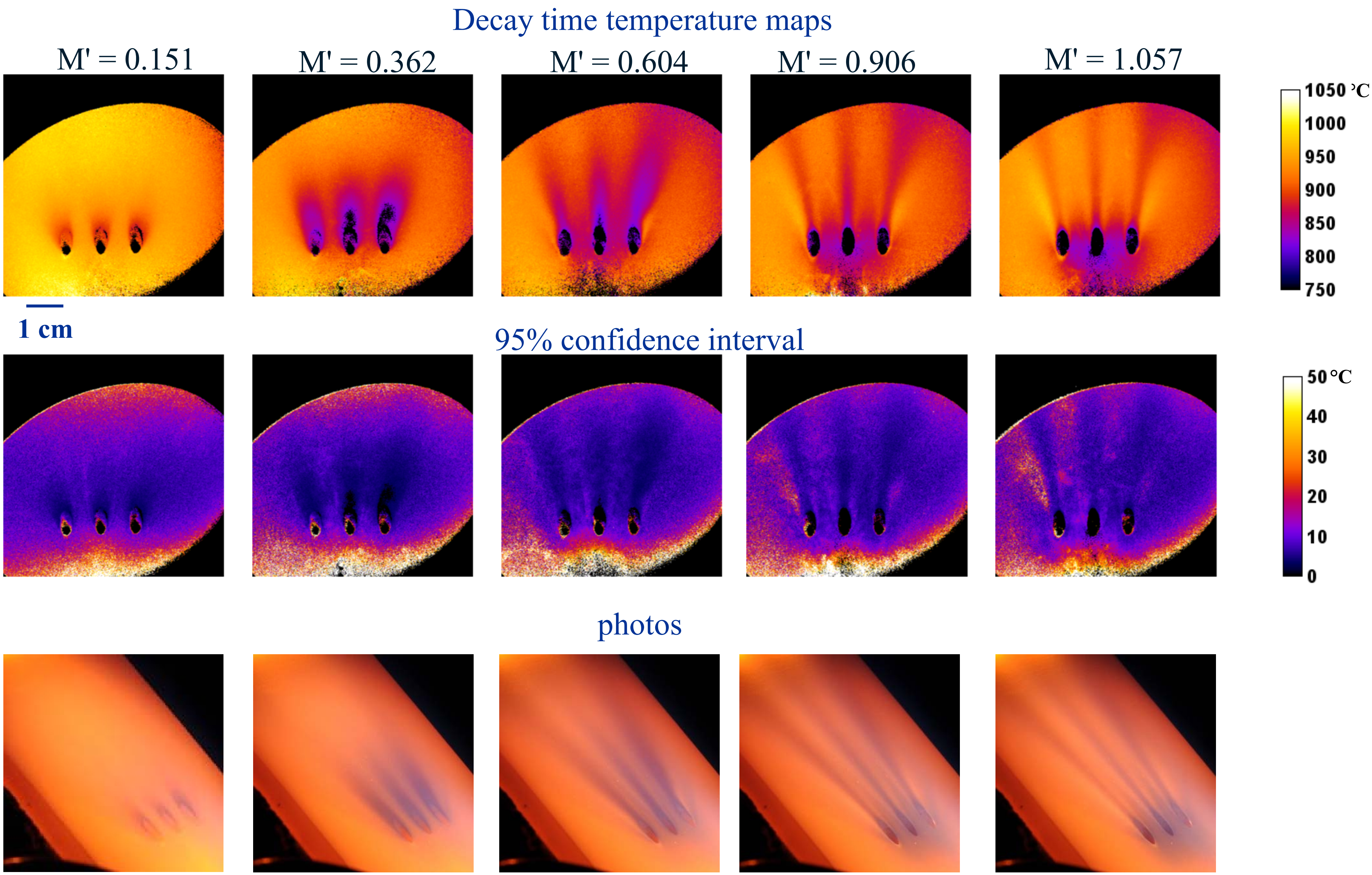


Rapidly increasing through-hole convection cooling effectiveness
Diminishing air film cooling effectiveness with air jet lift-off
Appearance of vortex-induced hot streaks

Upstream through-hole convective cooling

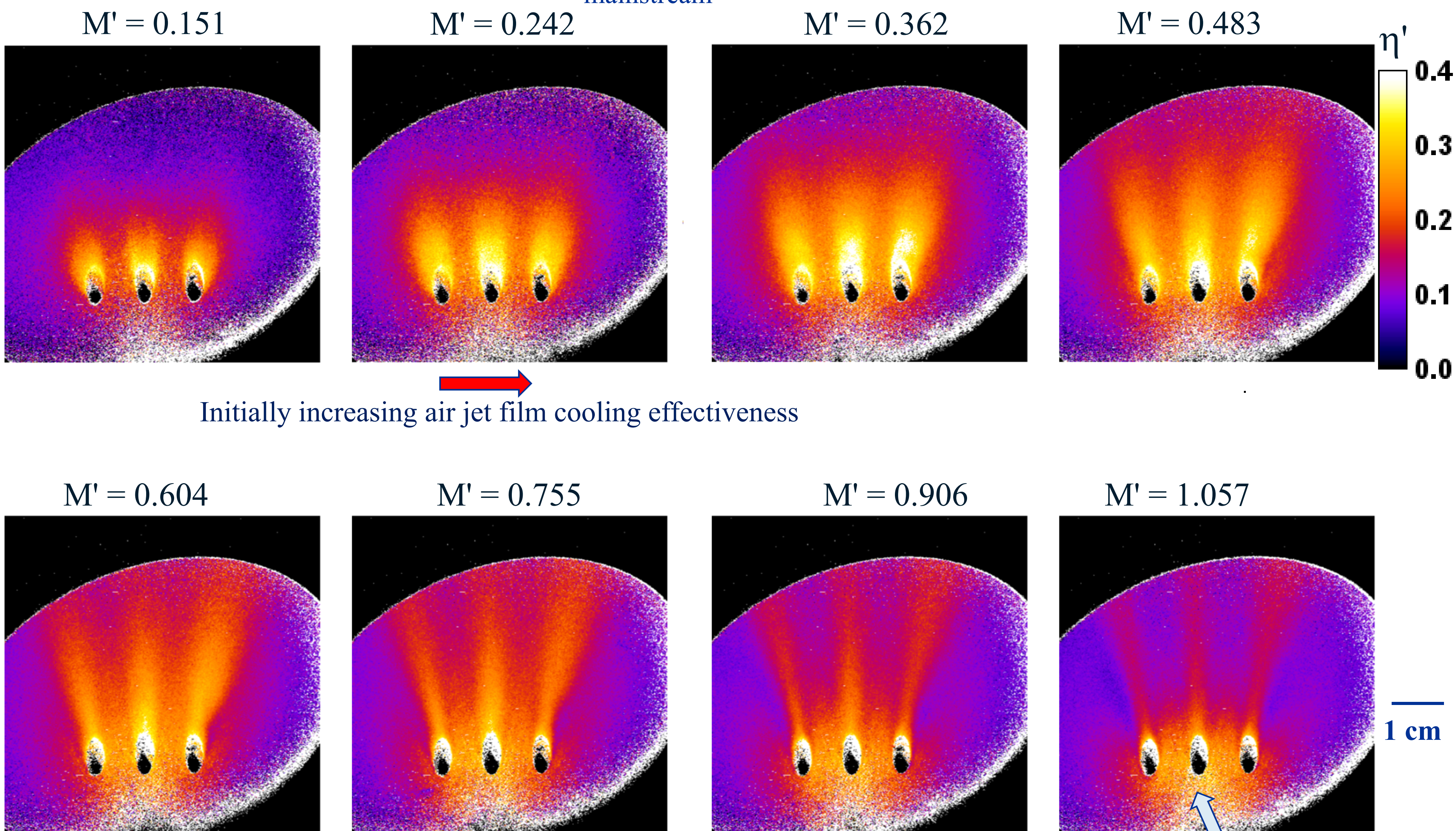
Burner Rig 2D Temperature Maps

$T_{mainstream} = 1604°C$



Burner Rig 2D Cooling Effectiveness Maps

$T_{mainstream} = 1604°C$



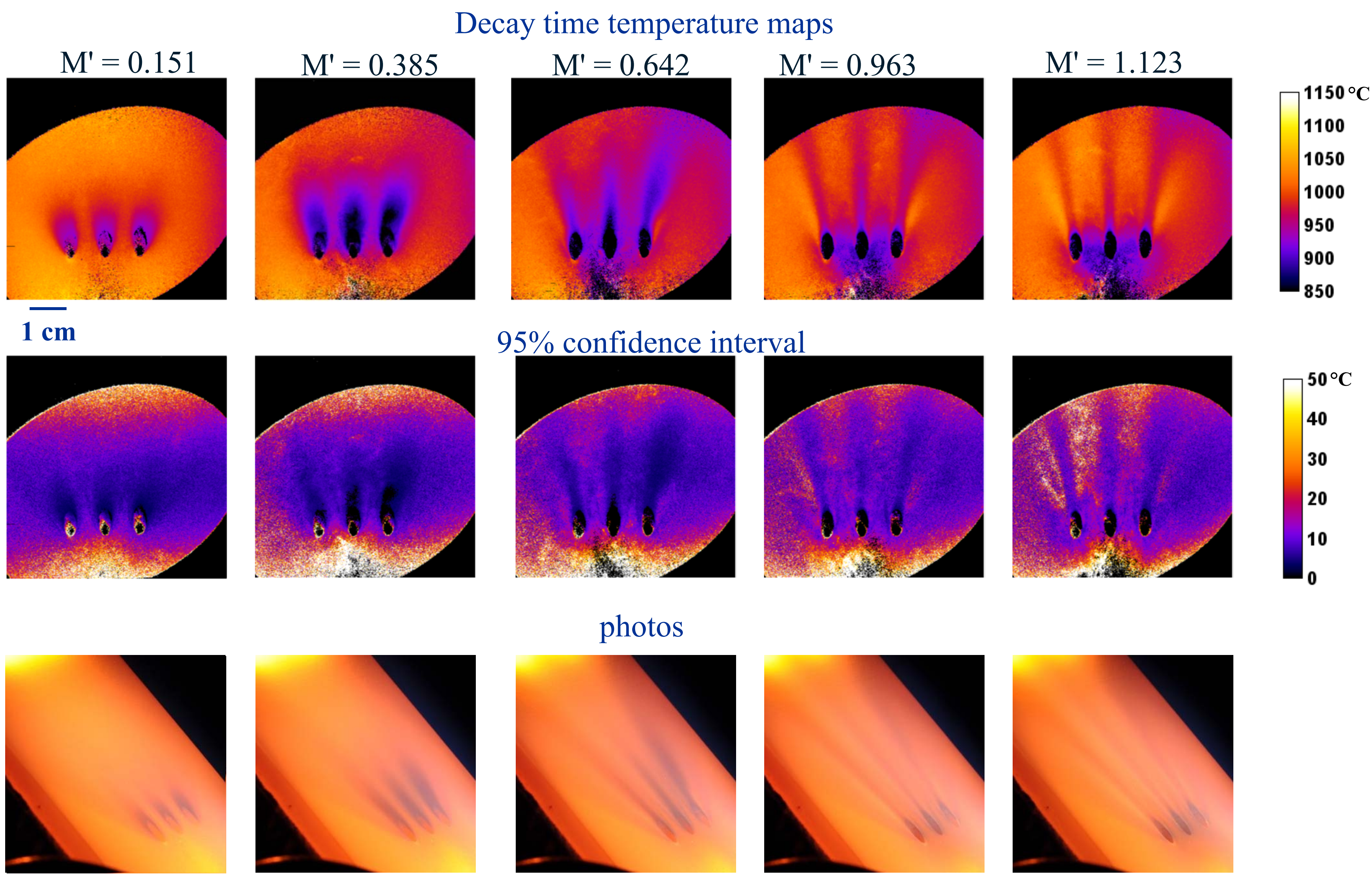
Initially increasing air jet film cooling effectiveness

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

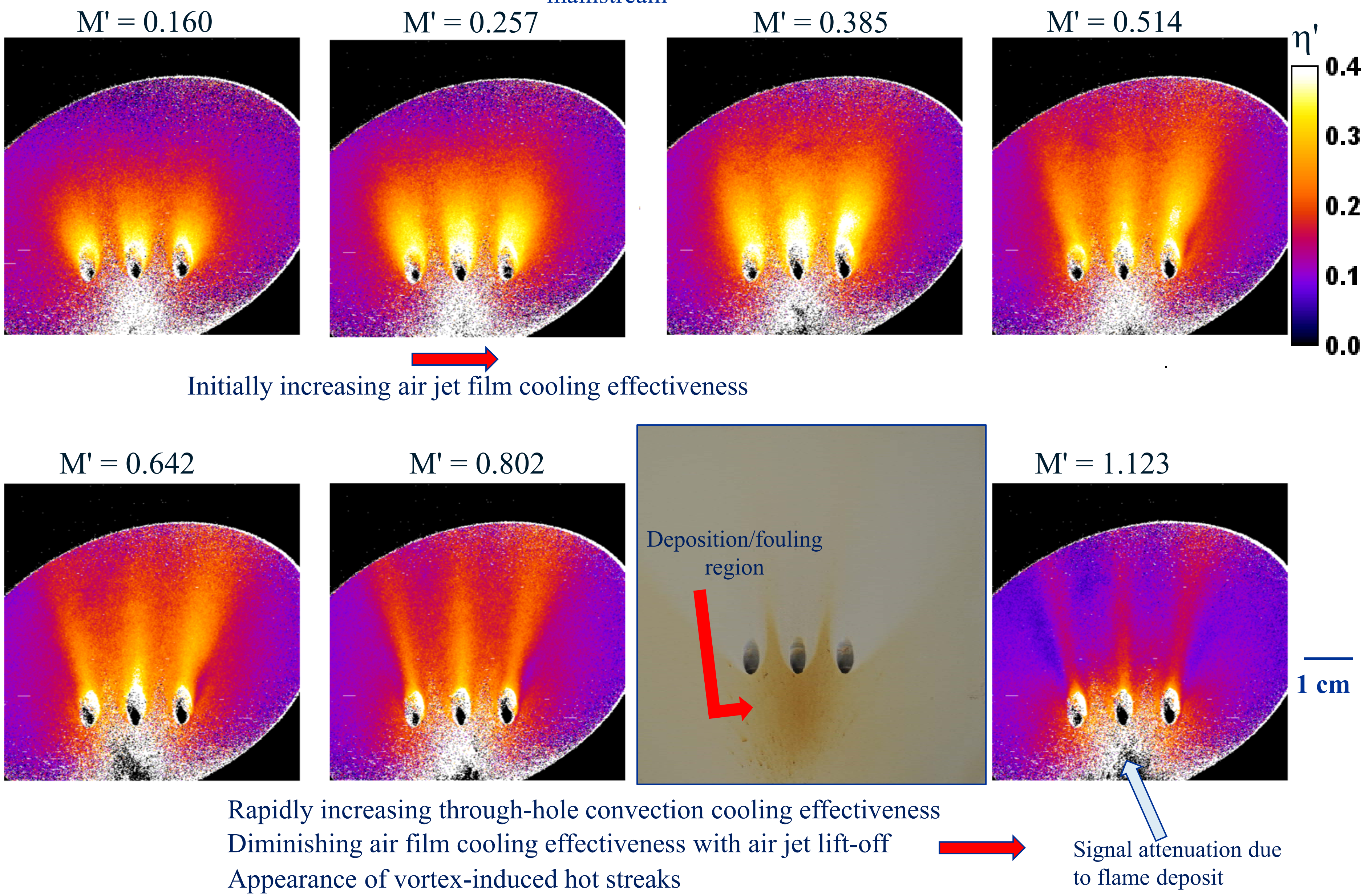
Burner Rig 2D Temperature Maps

$T_{mainstream} = 1722°C$

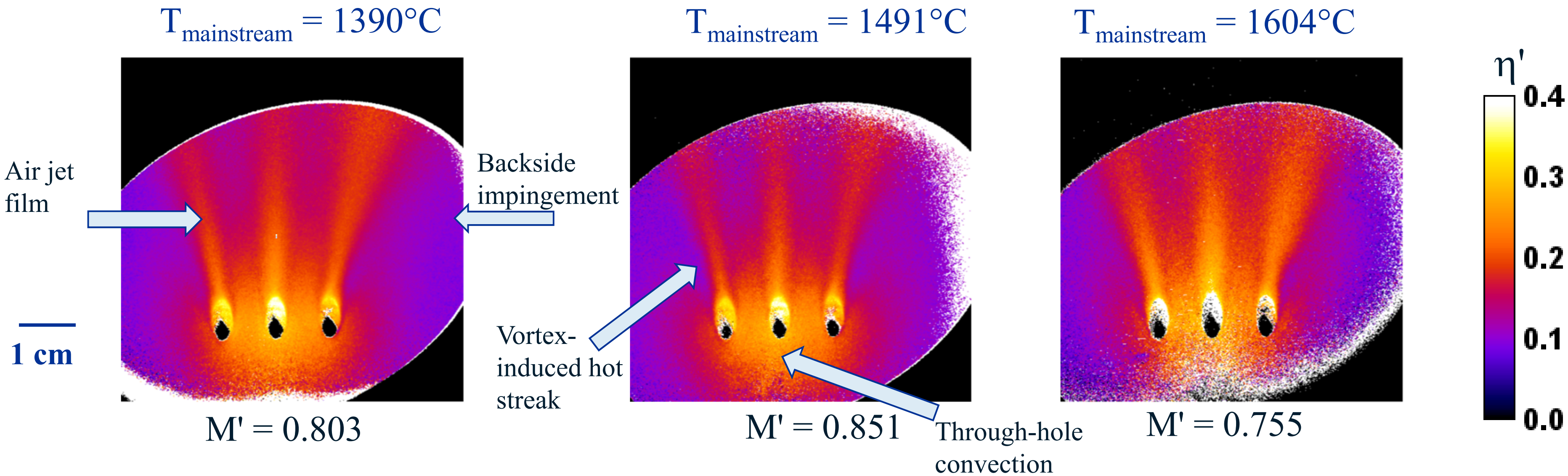


Burner Rig 2D Cooling Effectiveness Maps

$T_{mainstream} = 1722°C$



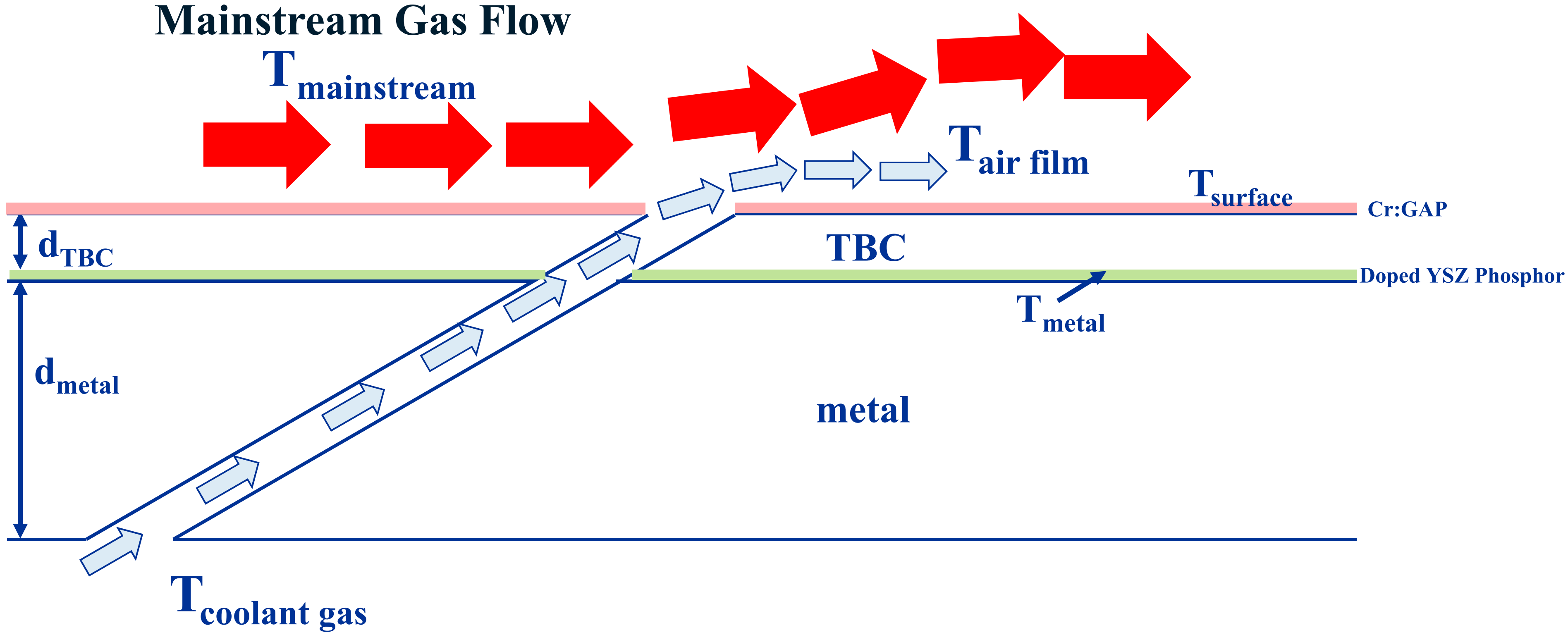
Combined Cooling Effects Summary



- 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

Acknowledgment

- Funding from NASA Transformative Tools & Technologies (TTT) Project under the Transformative Aeronautics Concepts Program (TACP)