National Aeronautics and Space Administration

Temperature Mapping Above and Below Air Film-Cooled Thermal Barrier Coatings Using Phosphor Thermometry

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Motivation for Evaluating Combined TBC + Air-Film Cooling

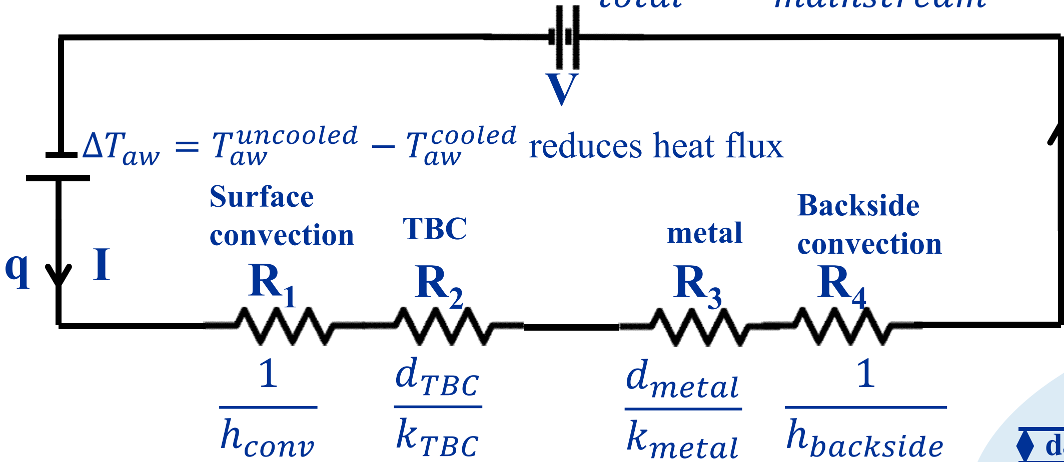
- TBC and air film cooling effectiveness usually studied separately.
- TBC and air film cooling contributions to cooling effectiveness are interdependent and are not simply additive.
- Combined cooling effectiveness must be measured to achieve optimum balance between TBC thermal protection and air film cooling.
- Typically, air-film cooling effectiveness is measured at TBC surface when cooling effectiveness at the underlying metal surface is more relevant.

Objectives

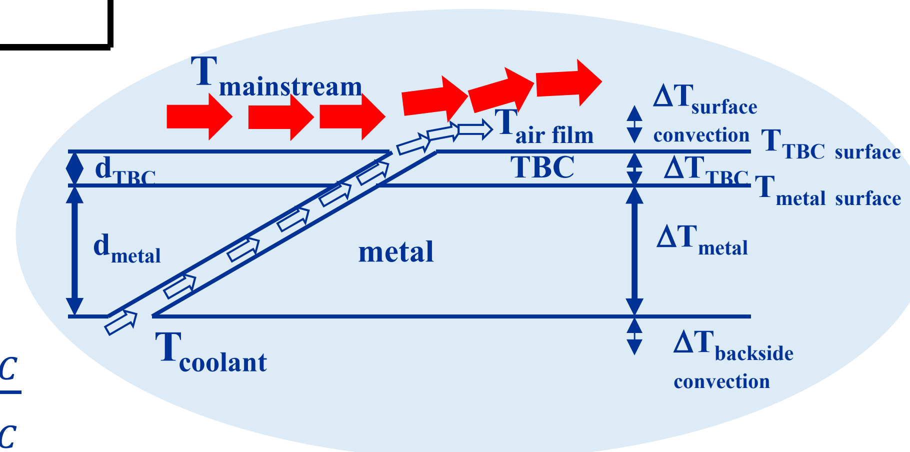
- Experimentally map temperatures above and below TBC during air-film cooling. Compare air film cooling effectiveness above and below TBC.
- Examine interplay between air film cooling, backside convection cooling, and in-hole convective cooling for TBC-coated substrate.

Heat Transport Through Turbine Blade/Vane

$\Delta T_{total} = T_{mainstream} - T_{coolant}$ drives heat transport (not q)



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



$$T_{TBC\,surface}^{cooled} = T_{mainstream} - \Delta T_{aw} - \frac{q}{h_{conv}}$$

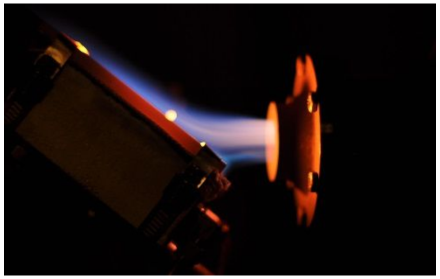
$$T_{metal}^{cooled} = T_{mainstream} - \Delta T_{aw} - \frac{q}{h_{conv}} - q\frac{d_{TBC}}{k_{TBC}}$$

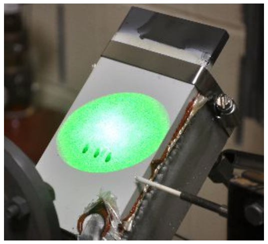
$$\frac{T_{metal}^{uncooled} - T_{metal}^{cooled}}{T_{TBC\,surface}^{uncooled} - T_{TBC\,surface}^{cooled}} = \frac{\frac{d_{metal}}{k_{metal}} + \frac{1}{h_{backside}}}{\frac{d_{TBC}}{k_{TBC}} + \frac{d_{metal}}{k_{metal}} + \frac{1}{h_{backside}}}$$

- **TBC can negate much of the effectiveness of air film cooling at metal surface beneath TBC.**
- **Experimental measurements of combined cooling effectiveness at TBC and metal surfaces are needed to evaluate TBC/air-film-cooling tradeoffs.**
    - **Air film cooling is prime reliant, TBC is not.**
    - **TBC does not penalize engine efficiency, air film cooling does.**

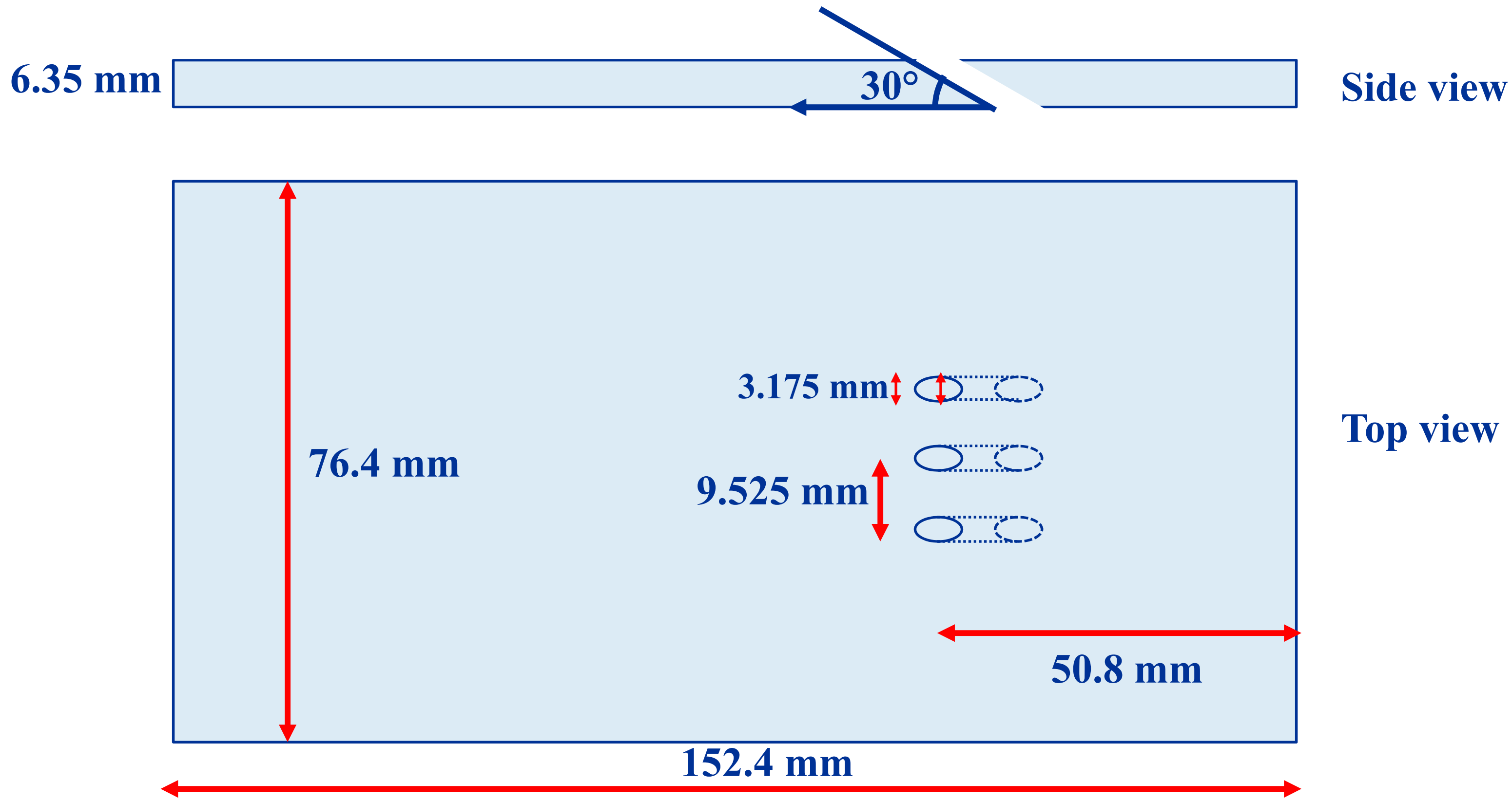
Approach

- Perform measurements in NASA GRC Mach 0.3 burner rig.
  - Vary flame temperature (1150 to 1722 °C) and blowing ratio (0 to 1.7).
- Perform measurements on TBC-coated superalloy plate with scaled up simple cooling hole geometry.
- Perform 2D temperature mapping using luminescence decay based phosphor thermometry.
  - Unbiased by emissivity changes and reflected radiation. ✓
  - Can be utilized for temperature mapping at surface of OR at bottom of TBC. ✓
  - Only applicable to steady state temperatures. ✗
- Selection of high emission intensity thermographic phosphors enables temperature mapping above or below TBC using luminescence lifetime imaging by simply broadening the excitation laser beam to cover the region of interest.
  - Ultrabright Cr(0.2%)-doped $GdAlO_3$ (GAP:Cr) for surface temperature mapping.
  - YSZ:Er(0.8%) for bottom of TBC temperature mapping and nonintrusive integration into TBC. Hypersensitive excitation at 517 nm for high emission intensity.

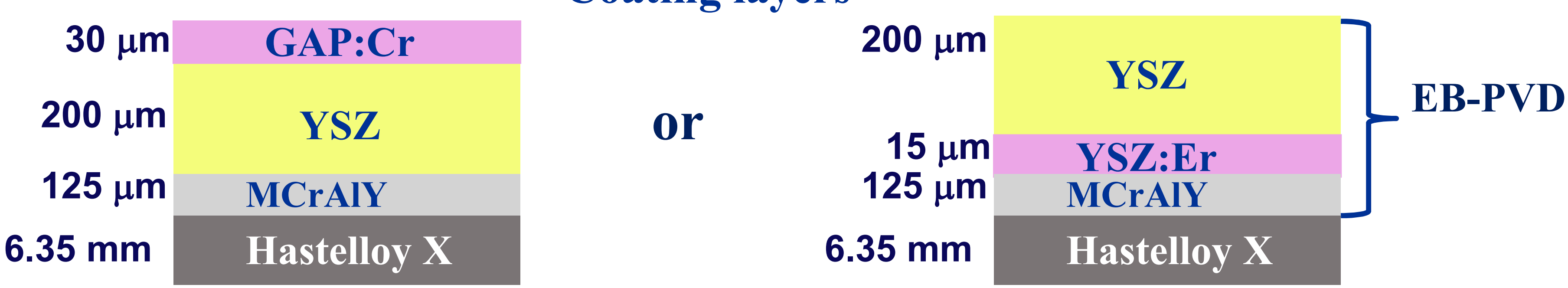




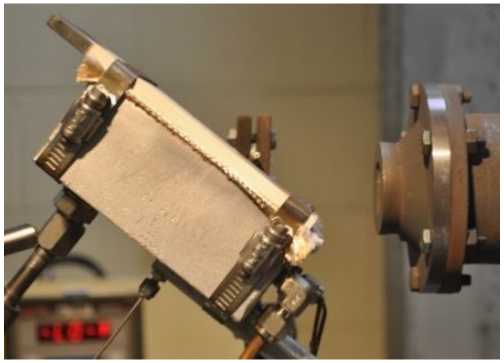
Cooling Hole Plate Geometry

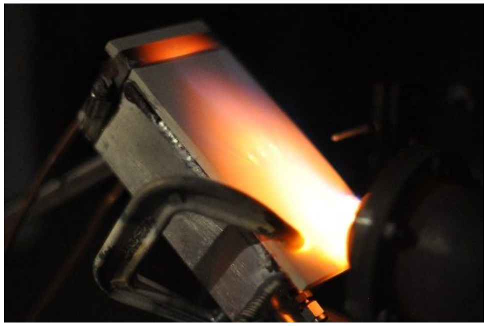


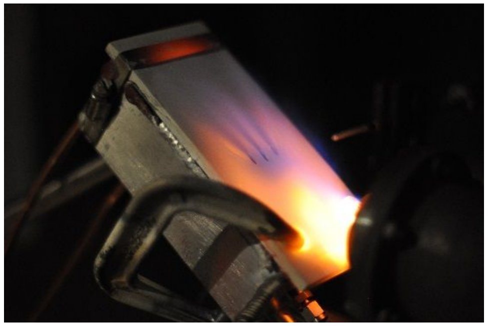
Coating layers

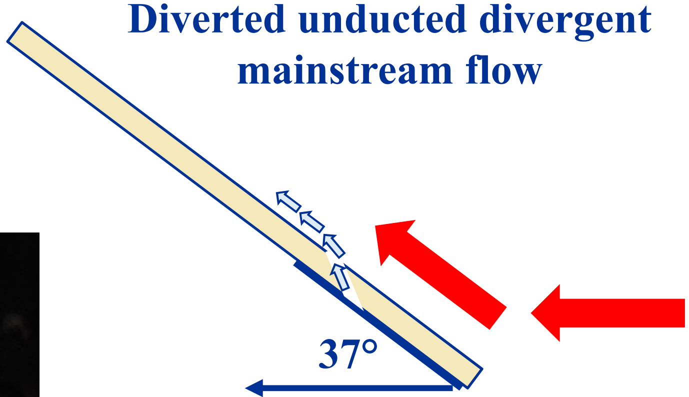


Burner Rig Cooling Effectiveness Measurements









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

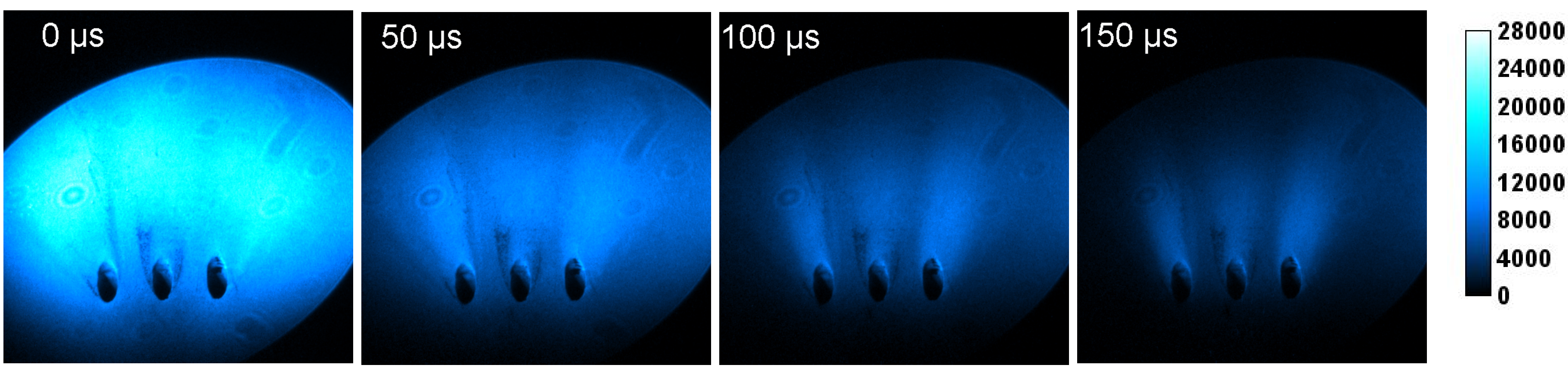
$$\eta' = \frac{T_{uncooled}^{TBC\ surface} - T_{cooled}^{TBC\ surface}}{T_{uncooled}^{TBC\ surface} - T_{coolant\ enter}} \qquad \Phi' = \frac{T_{uncooled}^{TBC\ bottom} - T_{cooled}^{TBC\ bottom}}{T_{uncooled}^{TBC\ bottom} - T_{coolant\ enter}}$$

- η' and Φ' no longer purely characterize air film cooling effects, but realistic characterization of combined cooling effects
- Measure η' & Φ' as a function of M'

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

2D Temperature Maps from Luminescence Lifetime Imaging

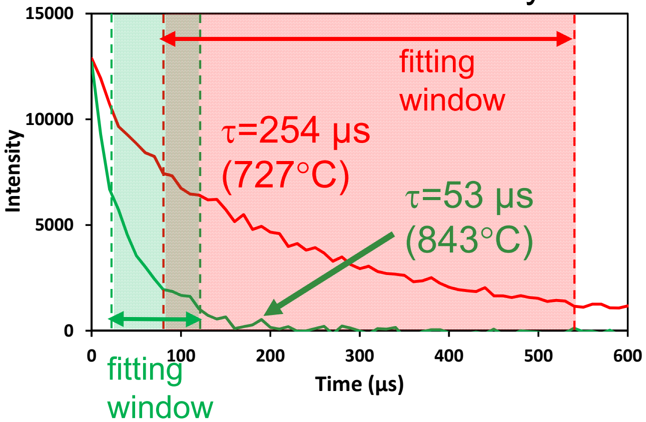
- Multi-step procedure:
  - Step 1: Collect time-gated image at predetermined delays after laser excitation pulse.
  - Step 2: Remove radiation background from each frame collected so that intensity in background-corrected exposure is purely due to luminescence emission.
  - Step 3: Assemble stack of background-corrected time-gated images over sequence of incremented delay times.



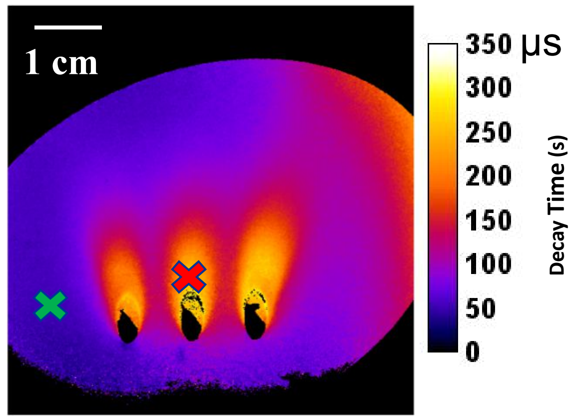
2D Temperature Maps from Luminescence Lifetime Imaging

– 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).

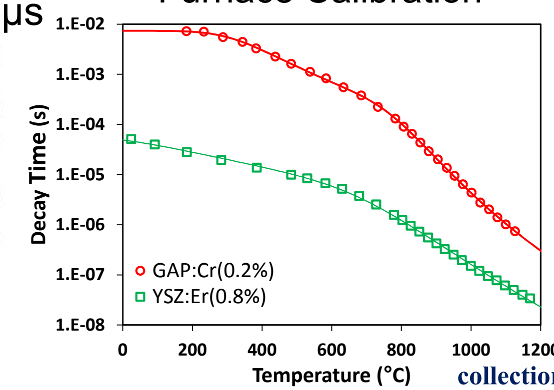
Individual Pixel Decays

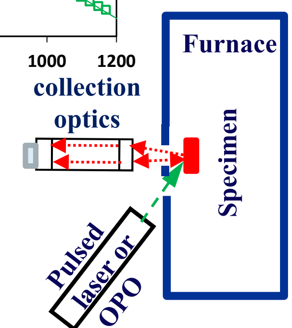


Decay Time Map



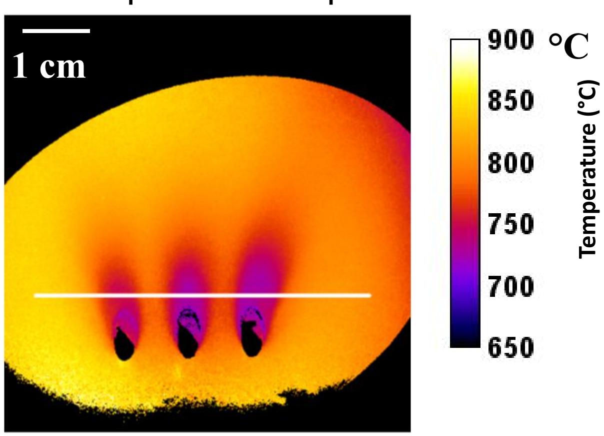
Decay Time vs. Temperature Furnace Calibration



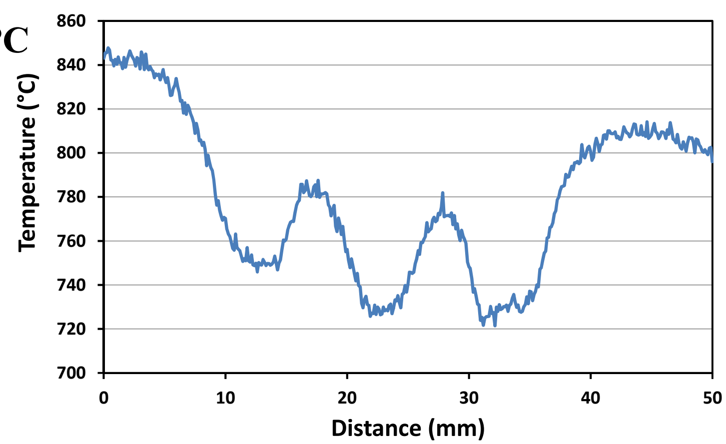


– Step 5: Use calibration data to convert decay time map to temperature map.

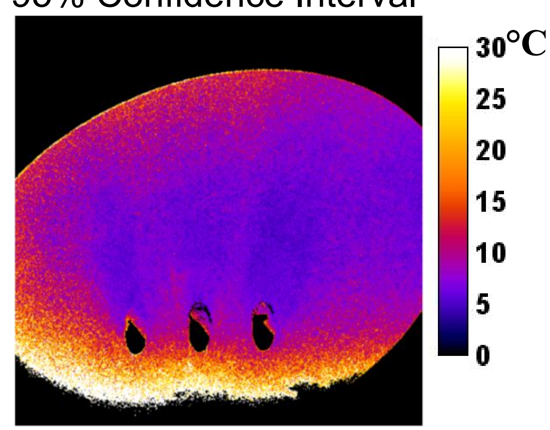
Temperature Map



Temperature Line Scan



95% Confidence Interval

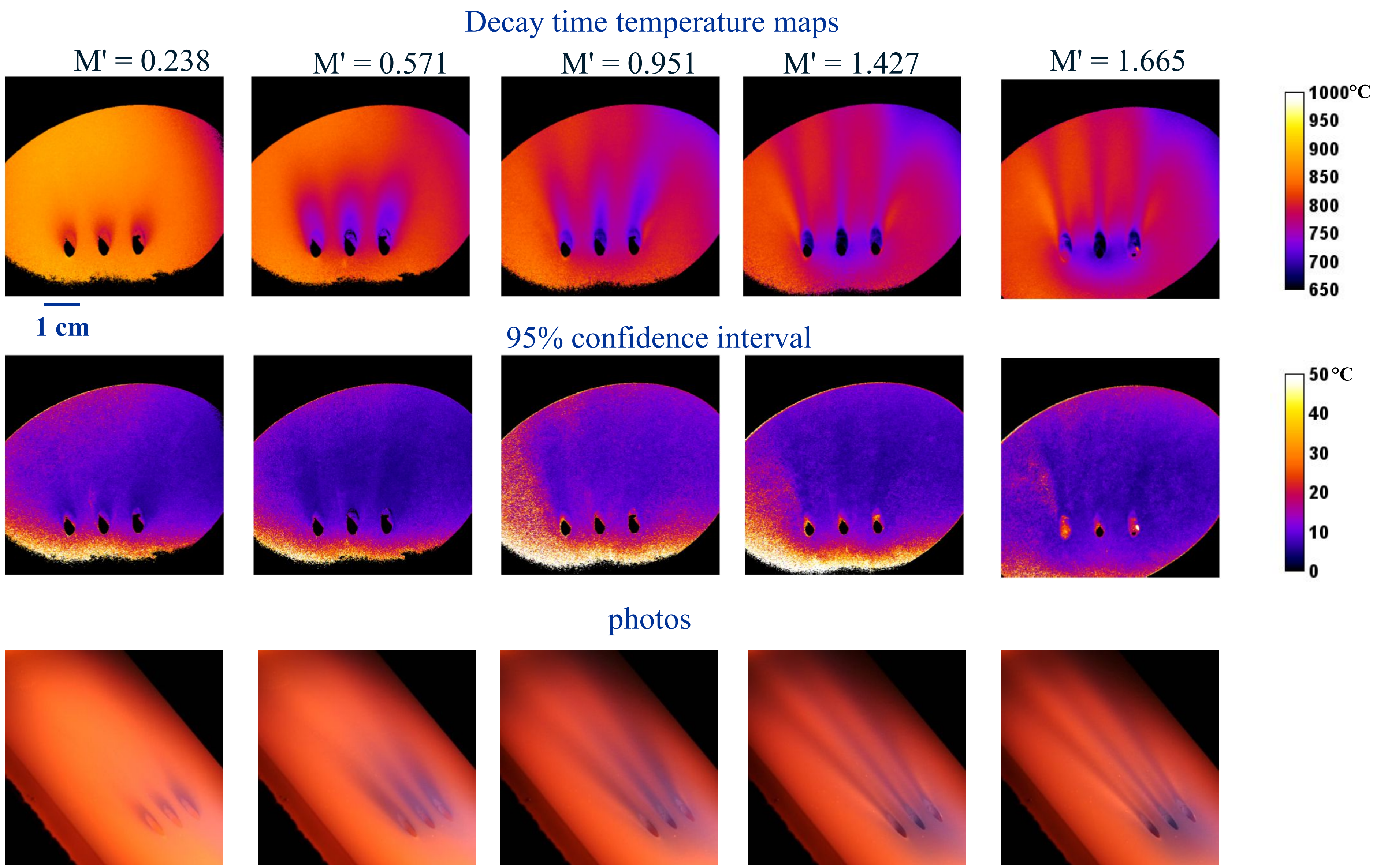


Air Film Cooling Effects at TBC Surface

Temperature and Cooling Effectiveness Maps

Burner Rig 2D Surface Temperature Maps

$T_{mainstream} = 1390°C$

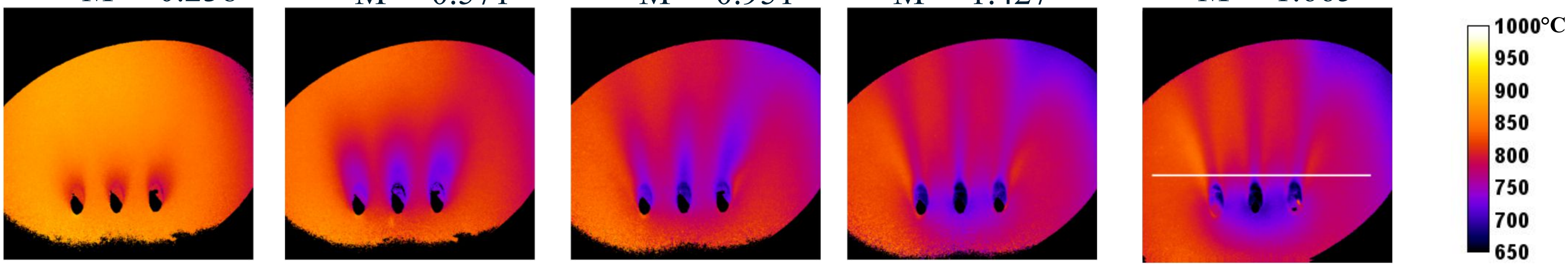


Burner Rig 2D Surface Temperature Maps

$T_{mainstream} = 1390°C$

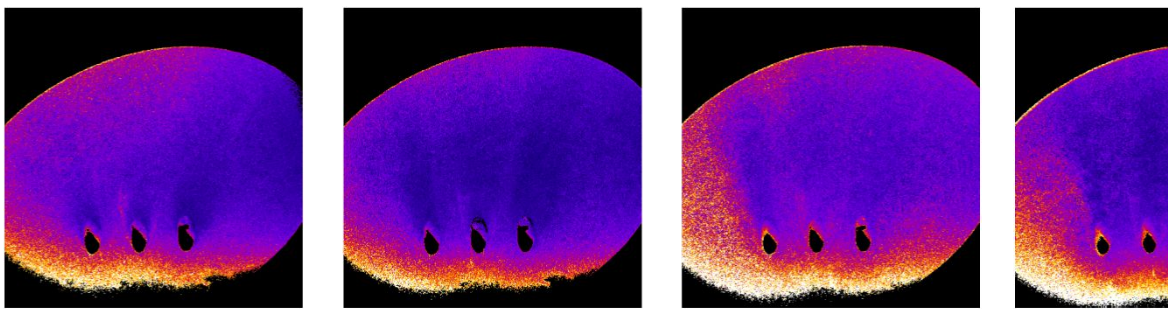
Decay time temperature maps

M' = 0.238 M' = 0.571 M' = 0.951 M' = 1.427 M' = 1.665

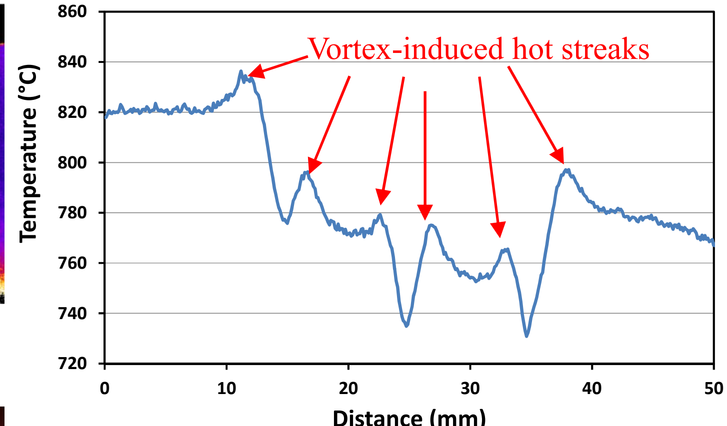


1 cm

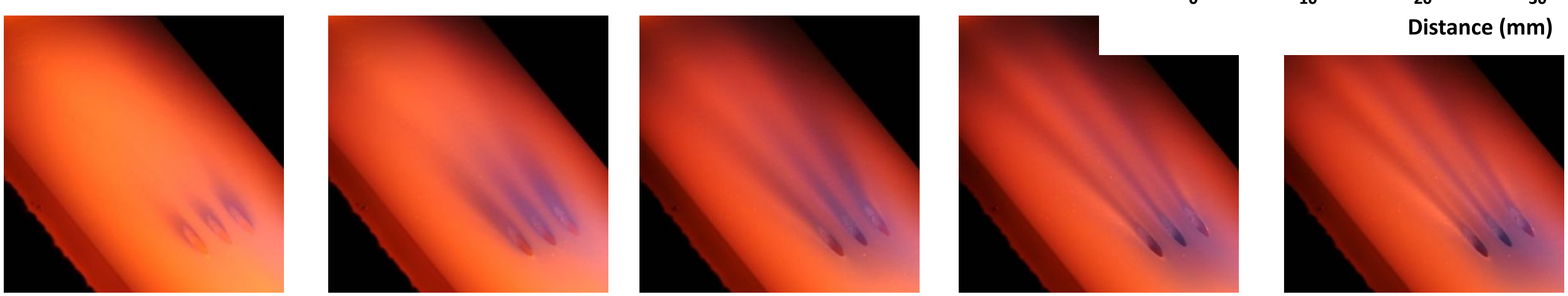
95% confidence interval



Temperature Line Scan

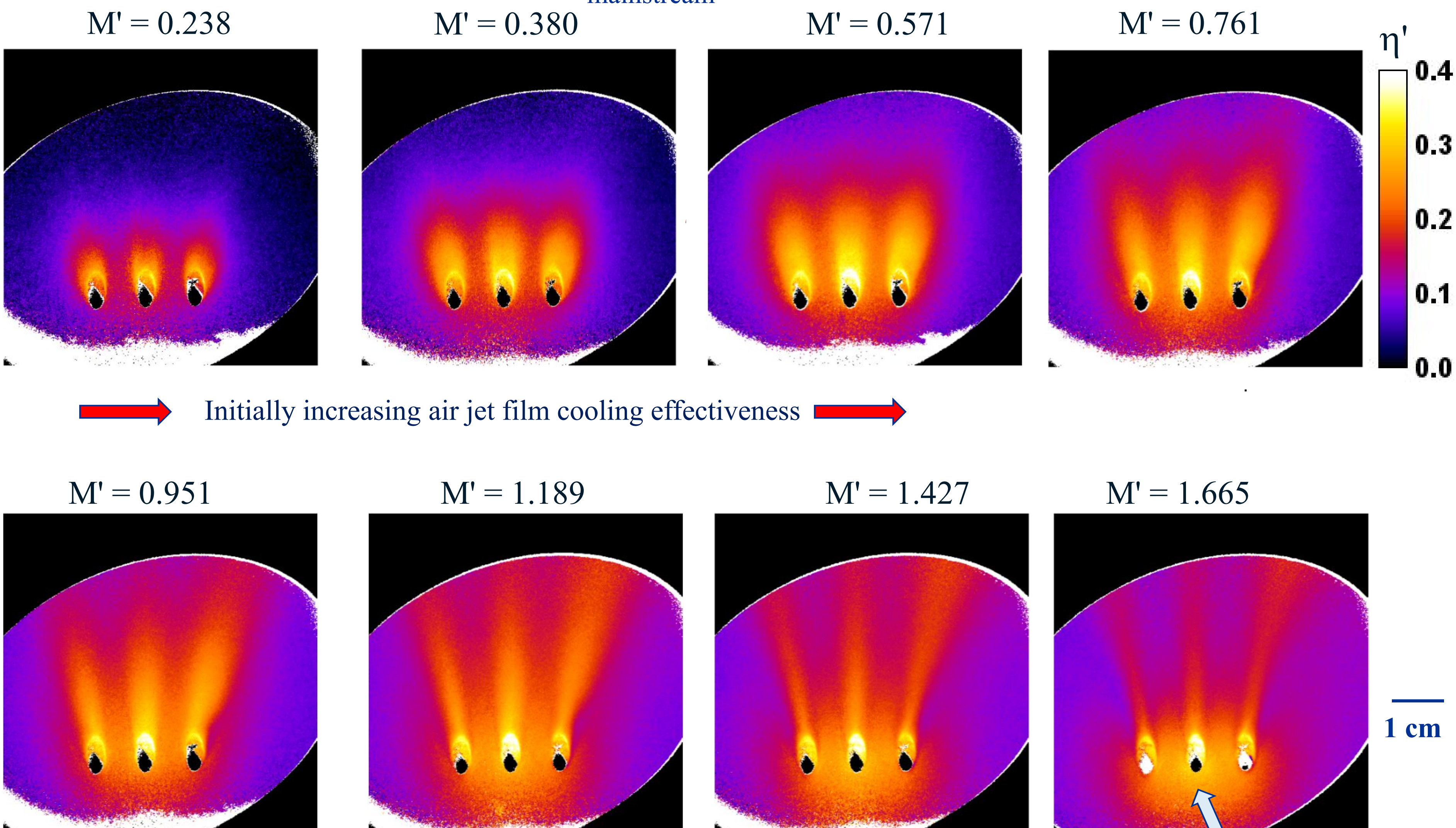


photos



Burner Rig 2D Surface Cooling Effectiveness Maps

$T_{mainstream} = 1390°C$



Initially increasing air jet film cooling effectiveness

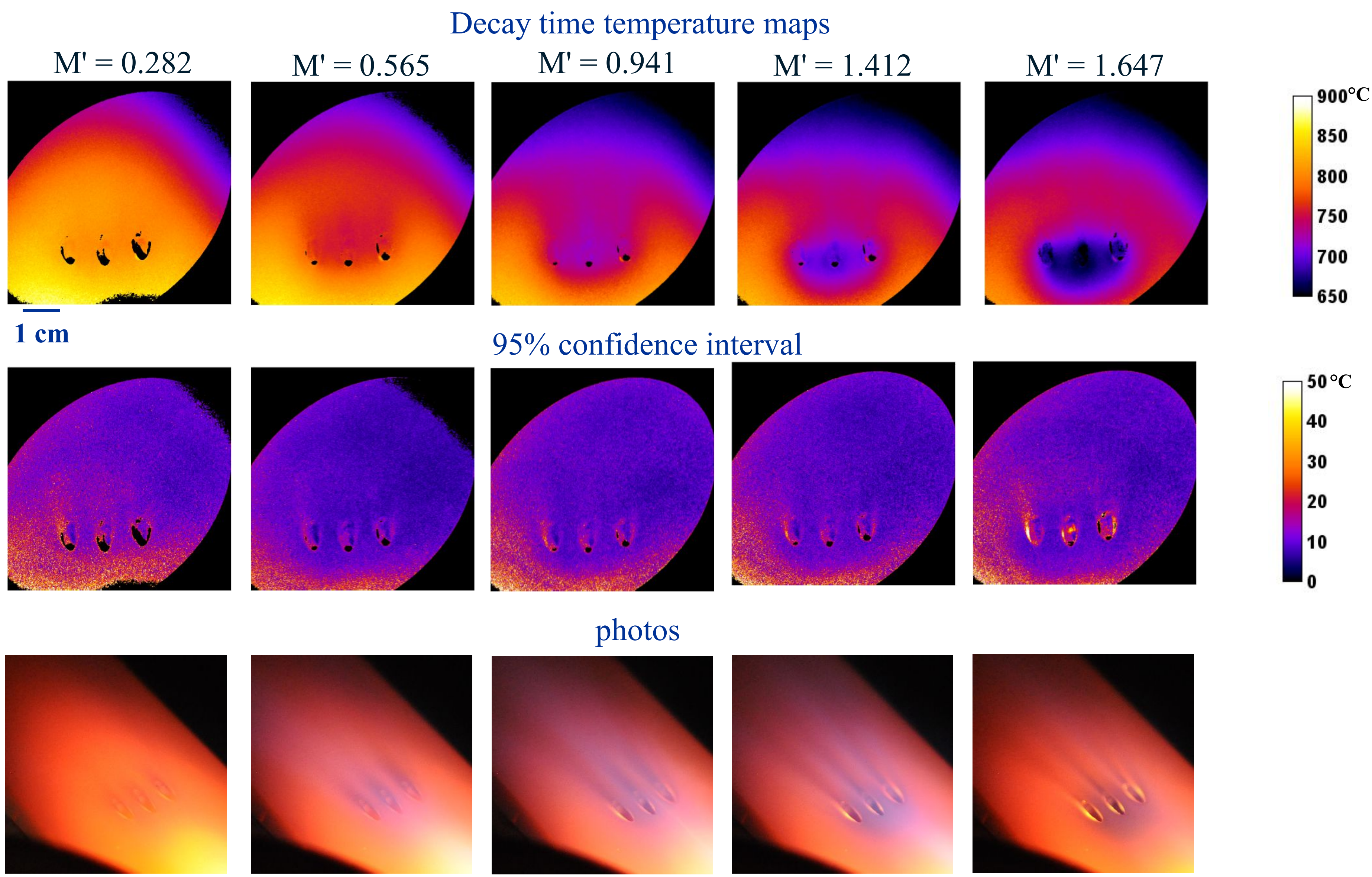
Diminishing air film cooling effectiveness with air jet lift-off
Appearance of vortex-induced hot streaks
Rapidly increasing in-hole convection cooling effectiveness

Upstream in-hole convective cooling

Air Film Cooling Effects Below TBC
Temperature and Cooling Effectiveness Maps

Burner Rig 2D Temperature Maps Below TBC

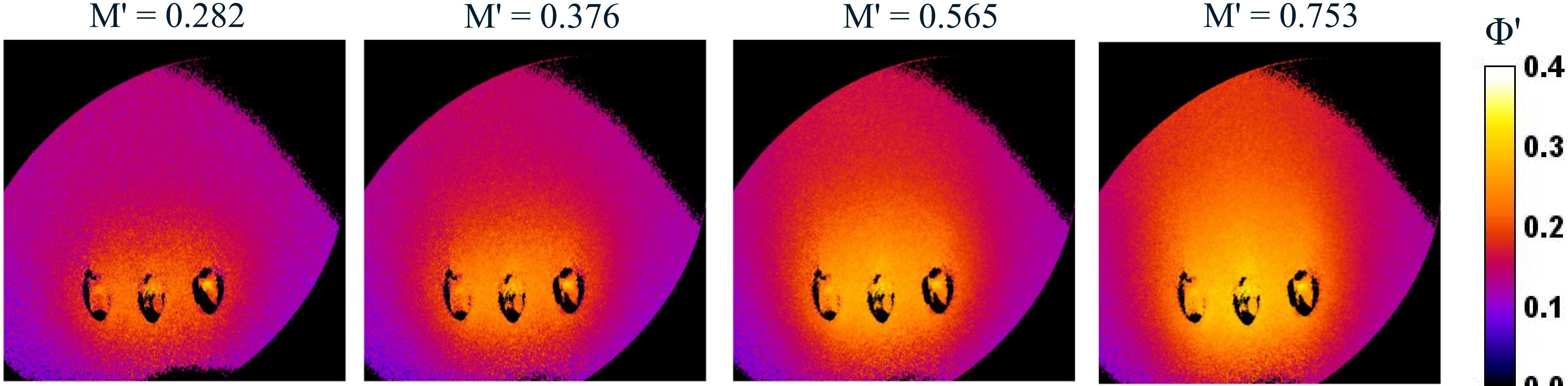
$T_{mainstream}$ =1355 °C



Burner Rig 2D Metal Cooling Effectiveness Maps

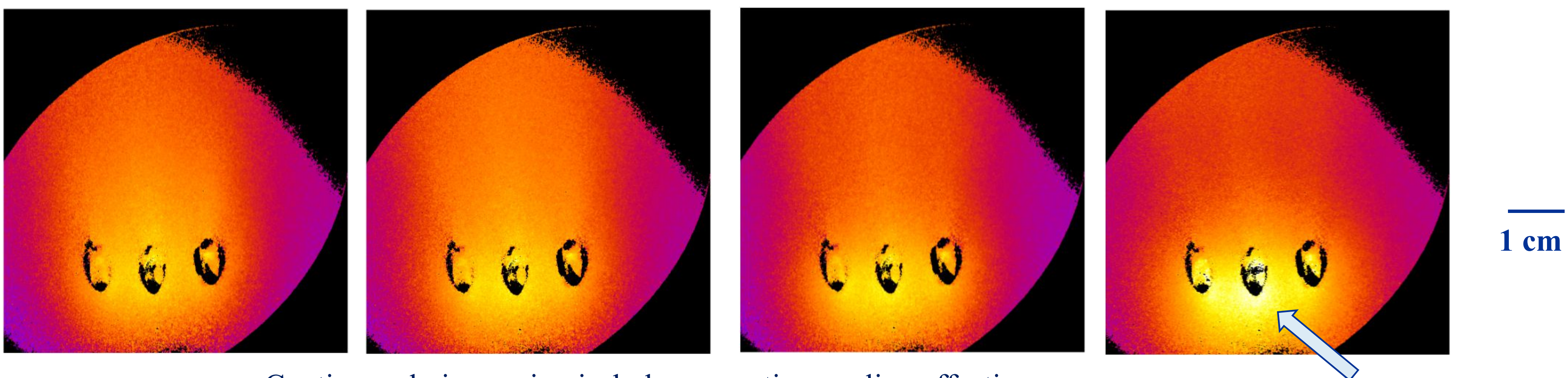
$T_{mainstream} = 1355\ °C$

M' = 0.282 M' = 0.376 M' = 0.565 M' = 0.753



In-hole convection cooling dominates over air film cooling even at low M.
Initially increasing air film cooling effectiveness.
Cooling from individual air jets indistinct.

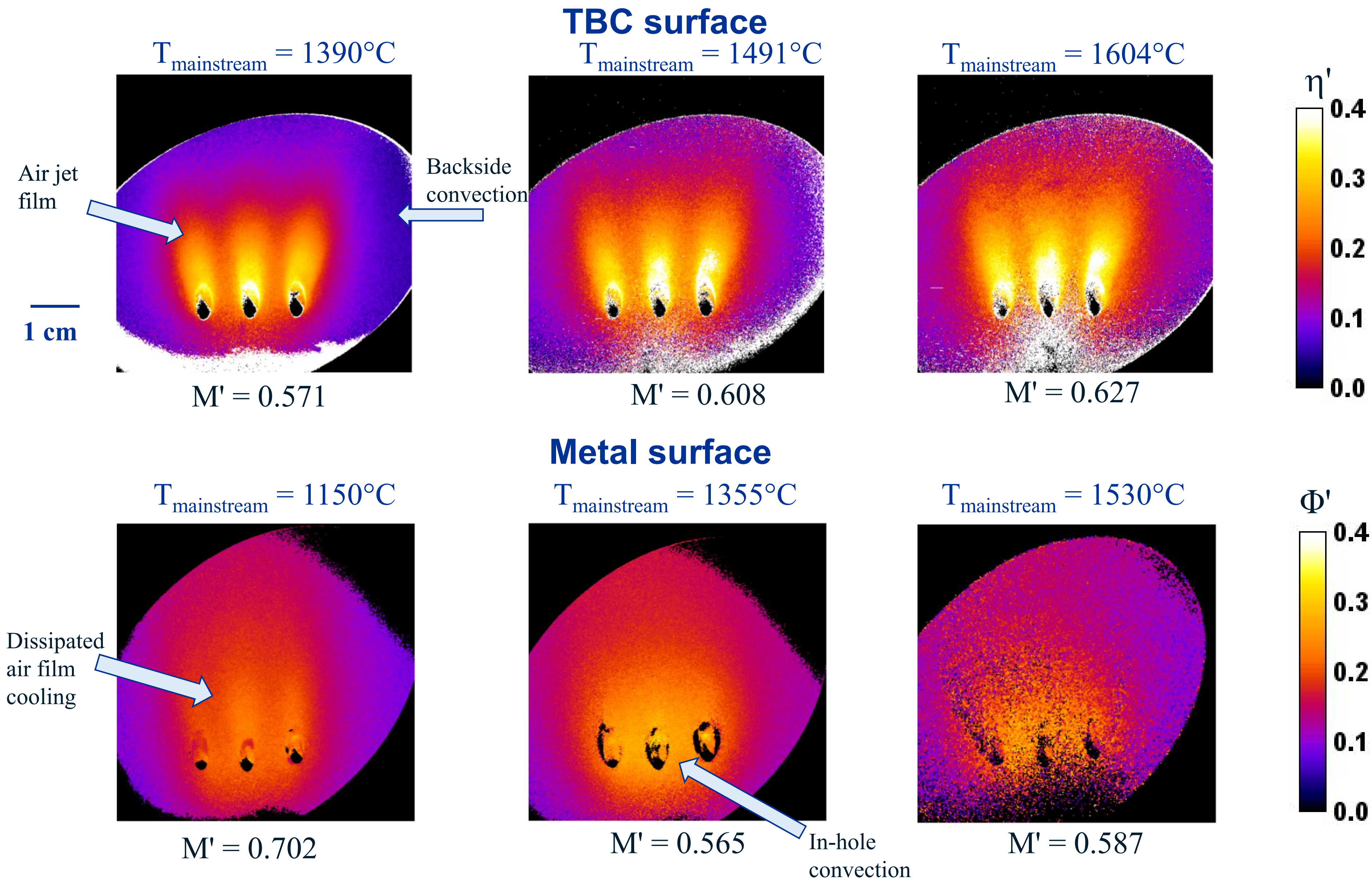
M' = 0.941 M' = 1.176 M' = 1.412 M' = 1.647



Continuously increasing in-hole convection cooling effectiveness.
Dissipating downstream cooling.
No evidence of of vortex-induced hot streaks.

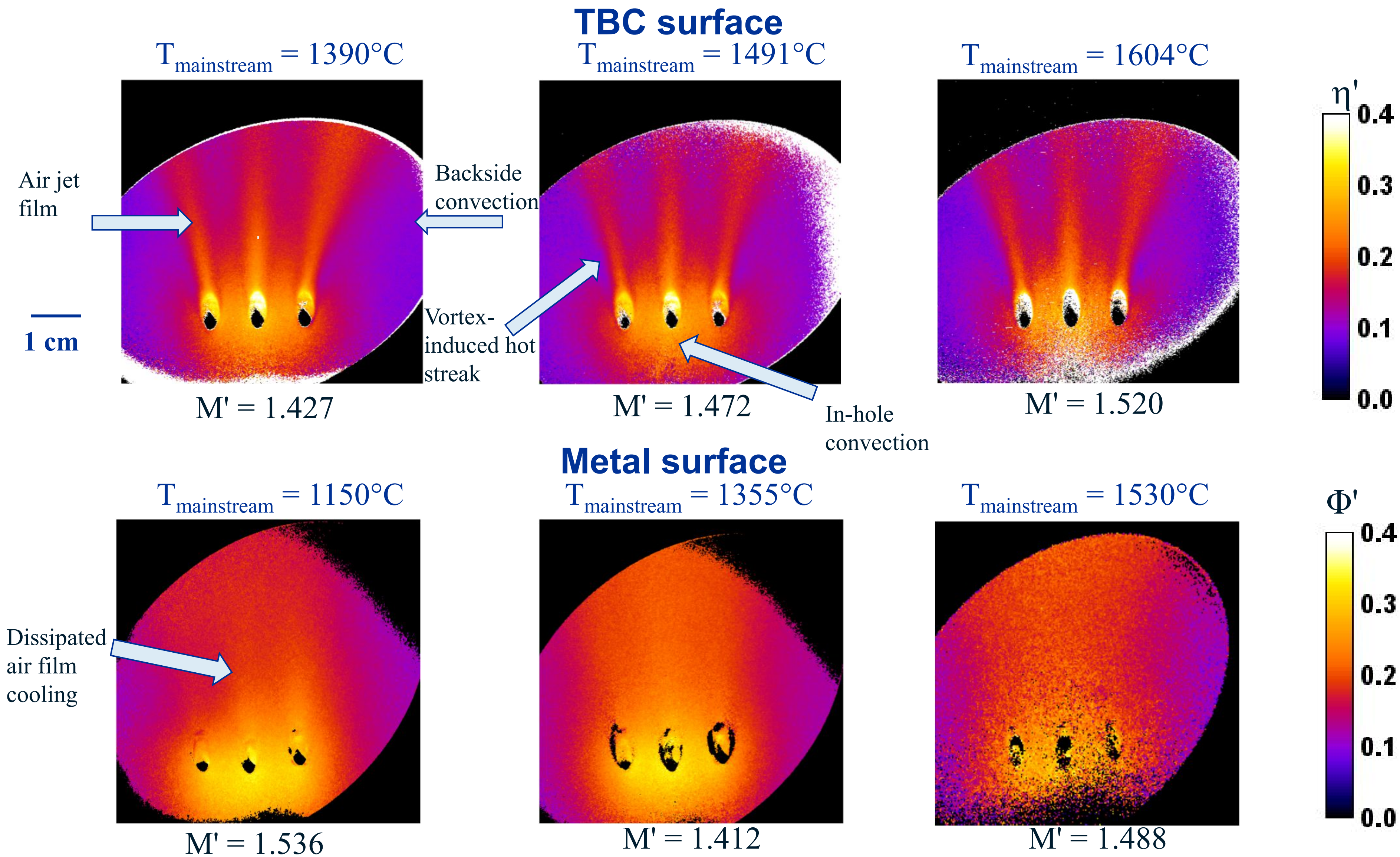
Upstream in-hole convective cooling

Combined Cooling Effects at Low M'



- Air film cooling by distinct air jets dominates at TBC surface.
- In-hole convection cooling dominates at metal surface.

Combined Cooling Effects at High M'



- Air film cooling diminishes due to air jet lift-off at TBC surface. Vortex-induced hot streaks appear.
- In-hole convection cooling continues to dominate at metal surface. Weaker air film cooling more uniform below TBC.

Combined Cooling Effects Summary

Air film cooling

TBC surface

- Effectiveness initially increases with increasing M, then diminishes with jet lift-off.
- Vortex-induced hot streaks appear along sides of cooling jets.

Metal surface

- Effectiveness also initially increases with increasing M, then diminishes with jet lift-off.
- Much weaker cooling effectiveness, dominated by in-hole convective cooling.
- Less distinct cooling from individual air jets.
- No vortex-induced hot streaks.

In-hole convective cooling

TBC surface

- Effectiveness increases rapidly at high M and surpasses air film cooling effectiveness.

Metal surface

- Dominant over air film cooling effectiveness even at low M.

- Effect of TBC on air cooling mechanisms
  - Significantly degrades air film cooling effectiveness.
  - Enhances in-hole convective cooling effectiveness – may be useful for showerhead cooling.

Conclusions

- Successfully demonstrated 2D temperature mapping by GAP:Cr and YSZ:Er 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
  - In-hole convection
  - Backside convection

Acknowledgment

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Implications?

- Current cooling hole design is directed to optimize air film cooling of surface (uniform cooling, anti-vortex, air jet suppression liftoff), but these benefits are lost underneath TBC.
  - For TBC-coated components, should cooling holes be designed for maximum in-hole convective cooling rather than optimized air film cooling?
- Primary benefit of TBC for combined cooling is to reduce cooling air flow requirements, not to increase temperature capability (cooling effects are more redundant than additive).