SAND2016-6264C

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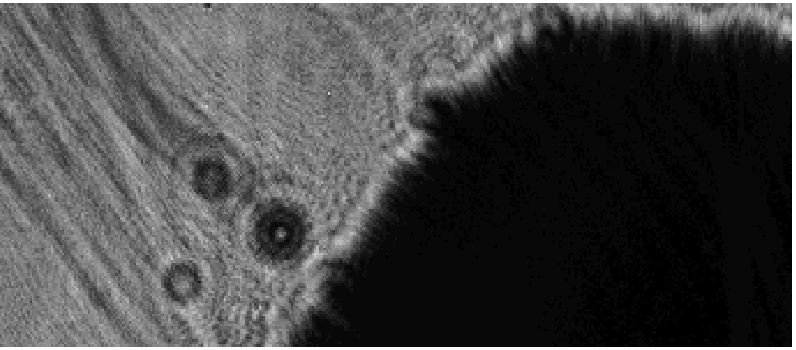

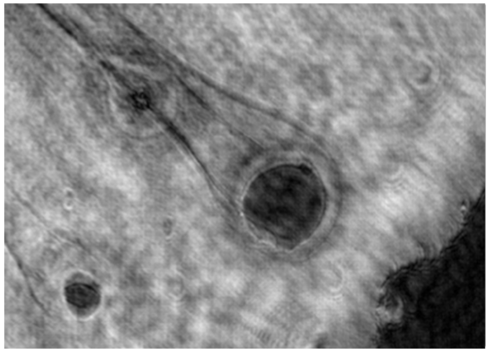

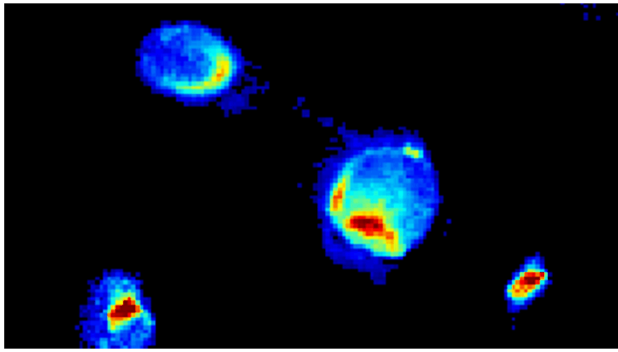

Digital Imaging Holography and Pyrometry of Aluminum Drop Combustion in Solid Propellant Plumes

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July 26th, 2016

Presentation LT4F.2

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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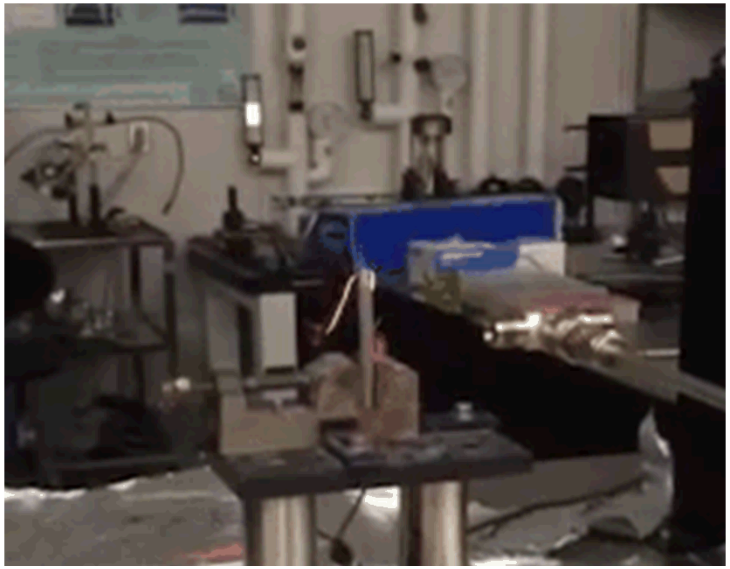
Motivation

http://www.cbsnews.com/news/rocket-crash-no-immediate-threat-to-station-but-cause-is-unknown/

Color video of burning propellant



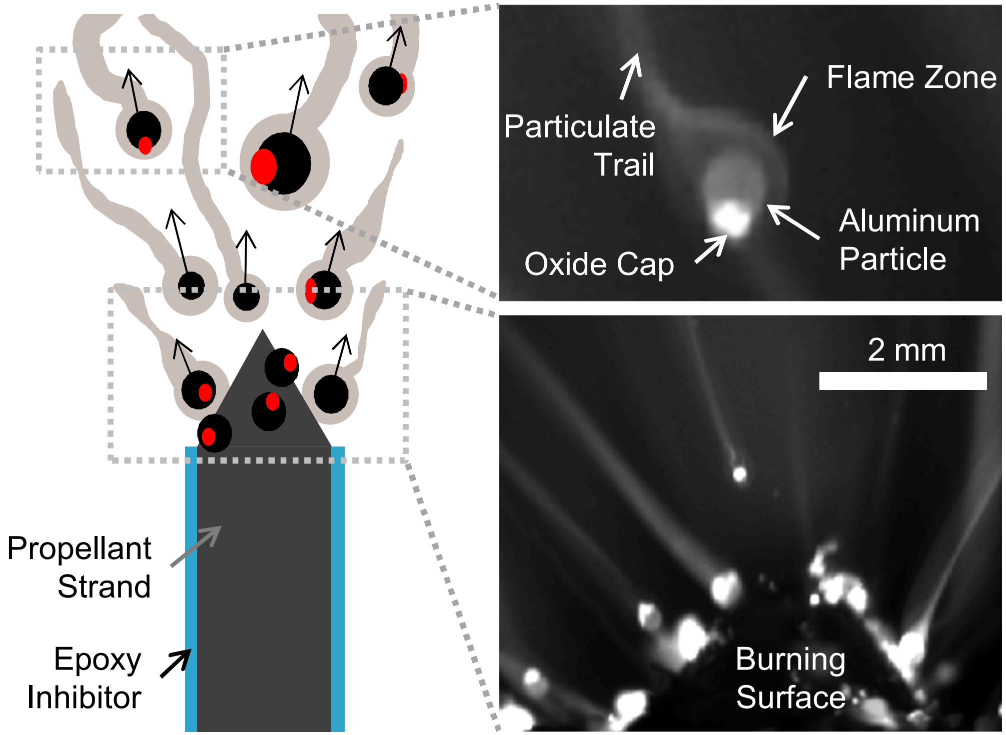
Problem:

- Rocket failures can lead to propellant fires
- Aluminum agglomeration at the surface yields large reacting drops with high damage potential
- Prediction requires knowledge of particle ***size*, *position*,** and ***temperature***

Goals:

- Making measurements in real propellant sticks
- Measuring the size of small particles that are out-of-focus

Approach



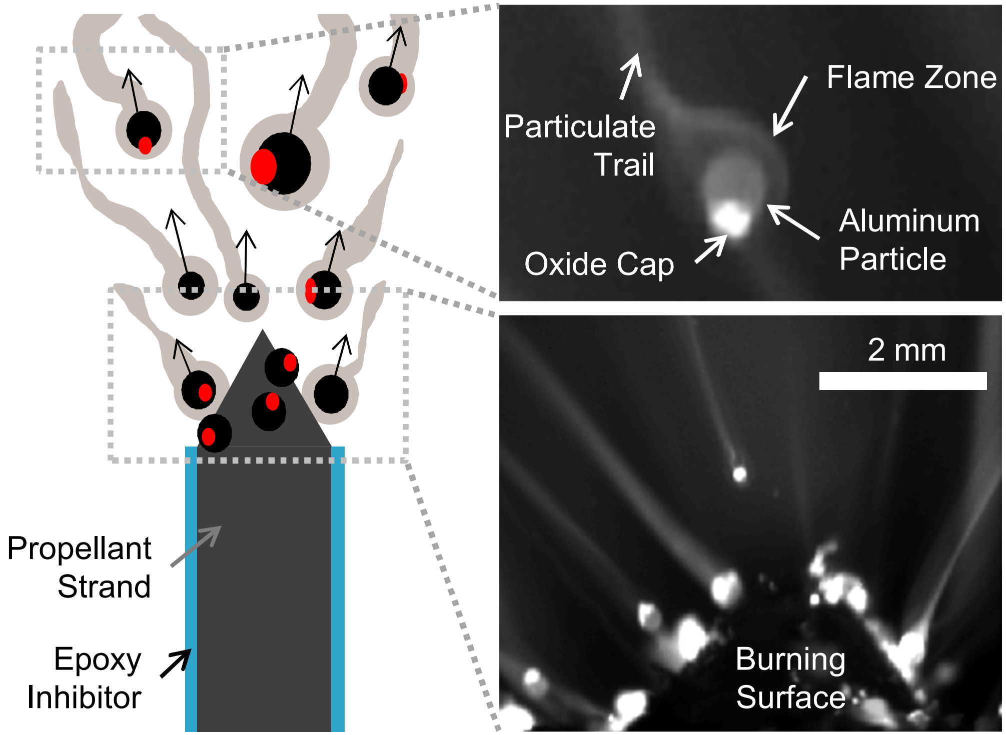
Propellant

- 6 mm diameter, 50 mm long
- 70 wt.% ammonium perchlorate oxidizer (AP)
- 20 wt.% aluminum particulate
- 10 wt.% inert hydroxyl terminated polybutadiene binder (HTPB)
- Epoxy inhibitor outer coating
- Burn rate ~1.4 to 1.6 mm/s

Combustion Process

- Propellant ignited with hot nichrome wire
- AP melts at 830 K, adiabatic flame temp 1205 K
- Al_2O_3 creates a flame holding effect, raising the flame temperature by ~1000 K
- Some Al particles (~30 µm) and Al_2O_3 shells melt at 2345 K
- These agglomerate into balls (~100 to 500 µm) and oxidizes to Al_2O_3 (caps and smoke) producing a flame zone (Al_2O_3 vaporizes at 3240 K)

Approach



High speed video of burning propellant

- Particle Size and Position?
- Particle Velocity?
- Particle Temperature?
- Gas Temperature and Composition?

Digital In-Line Holography (DIH)

Double Frame DIH

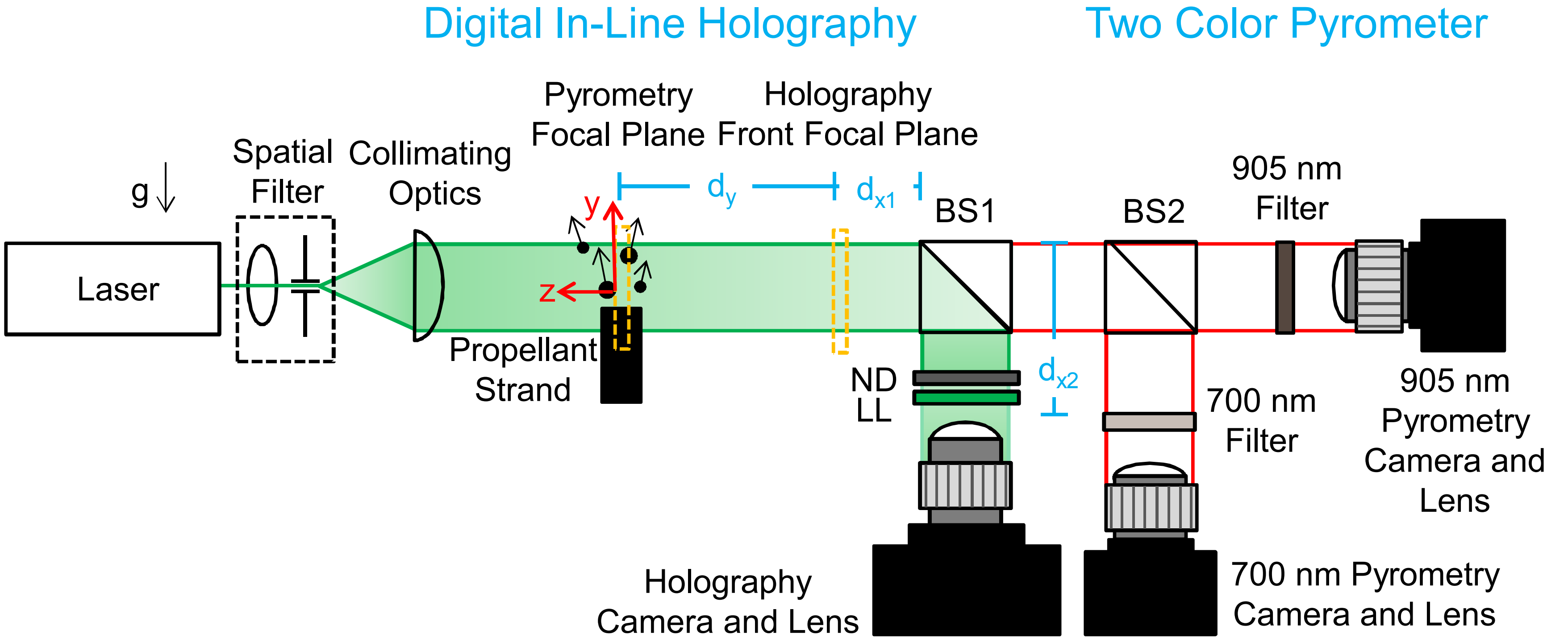
Two-Color Imaging Pyrometer

Coherent Anti-Stokes Raman Scattering (CARS)

DTh2E.3 (Thurs @ 12:15 PM)
D. Guildenbecher and P. Sojka
Digital in-line holography (DIH) to quantify the impact of a viscous drop on a thin film

LW5G.3 (Wed @ 5:45 PM)
S. Kearney and D. Guildenbecher
Temperature and oxygen measurements in a metallized propellant flame by hybrid fs/ps rotational coherent anti-Stokes Raman scattering

Experimental Setup



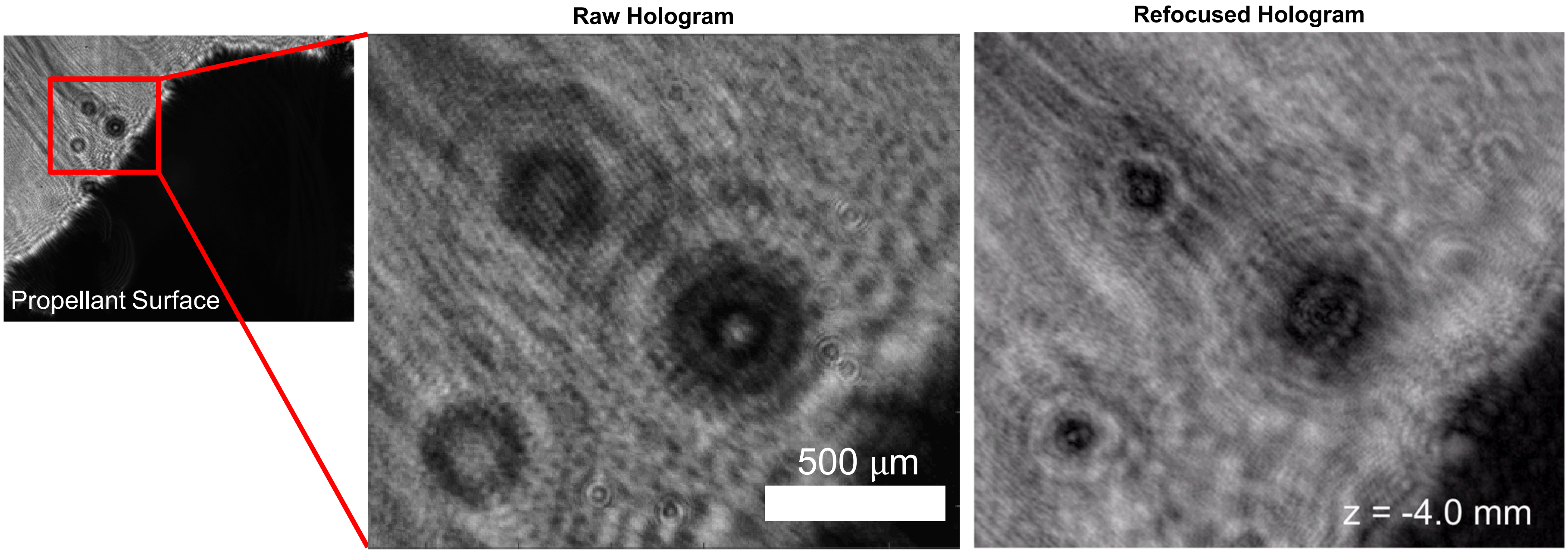
- $d_x = d_{x1}+d_{x2}$ = ~170 mm, d_y = 50 mm
- Double-pulsed ND:YAG laser (Continuum MiniLite PIV, 532 nm, 5 ns pulse duration, 40 µs pulse separation)
- Holography camera LaVision sCMOS (2560x2160 pixels, 6.5 µm pixel pitch, 16 bit depth, global shutter mode) and lens (Infnity K2 DistaMax with CF2 objective)
- Pyrometer cameras LaVision ProX 4M (2048x2048 pixels, 7.4 µm pixel pitch, 14 bit depth, global shutter mode) and lens (Navitar Zoom 7000 lenses, aperture full open)
- ND – Neutral Density Filter (OD2)
- LL – Laserline filter at 532 nm with bandwidth of 1 nm (Andover 532FS02-50)
- BS1 – Beam splitter, reflection @ 532 nm and transmission @ 650 to 900 nm
- BS2 – Beam splitter, reflection @ 650 to 750 nm and transmission @ 850 to 950 nm
- 700 and 905 nm filters with bandwidth of 10 nm

Digital In-Line Holography

Light propagation is described by the diffraction integral equation:

$$E(x,y,z)=\frac{1}{\lambda}\iint E(\xi,\eta,z=0)\frac{e^{-jkr}}{r}d\xi d\eta \quad \text{where: } r=\sqrt{(\xi-x)^2+(\eta-y)^2+z^2}$$

$E(x,h,0)$ ≡ complex amplitude at hologram plane = $h(x,h)\cdot E_r^*$
$E(x,y,z)$ ≡ refocused complex amplitude at optical depth z



Digital In-Line Holography

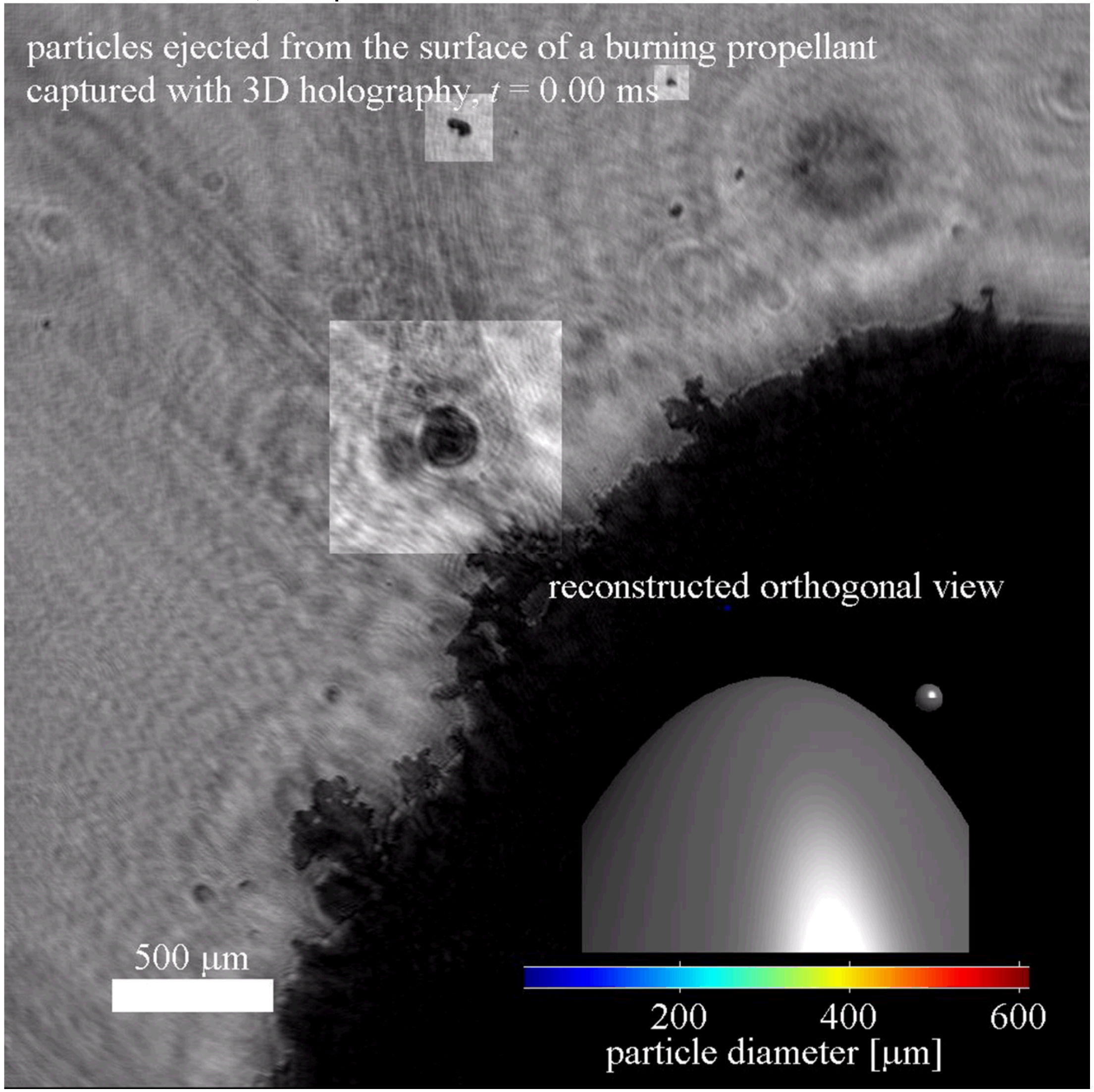
Recorded at 20,000 fps on Photron SA-Z with Coherent Verdi V6 Laser

Calibration

- Use a 1mm spacing dot grid
- Dewarp the images on 3 cameras to the same field of view

Detection Methods

- Find particle z-position by minimizing intensity and maximizing edge sharpness across a series of z-slices
- Find particle diameter by counting the number of dark pixels (minimum d = 11 μm)



D. Guildenbecher et. al., Applied Optics Vol. 55 (11), 2016.

Two-Color Pyrometer

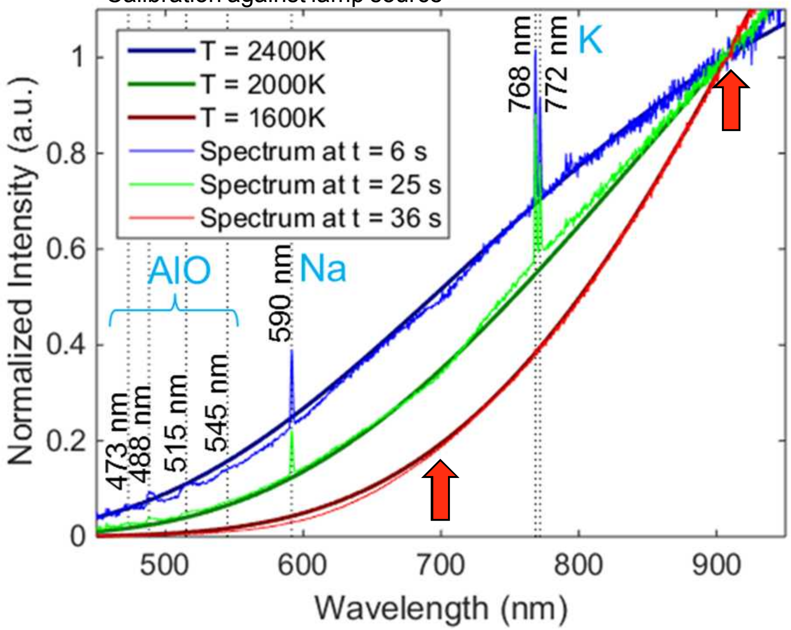
- Can use Plank's Law, assuming grey body emission
- Choose wavelengths to avoid combustion peaks
- If hc/λ >> kT, use Wein's approximation for each pixel:

$$T = \left[\frac{k}{hc}\frac{\lambda_1\lambda_2}{\lambda_2-\lambda_1}\left(\ln(R) - 5\ln\left(\frac{\lambda_1}{\lambda_2}\right)\right)\right]^{-1}$$

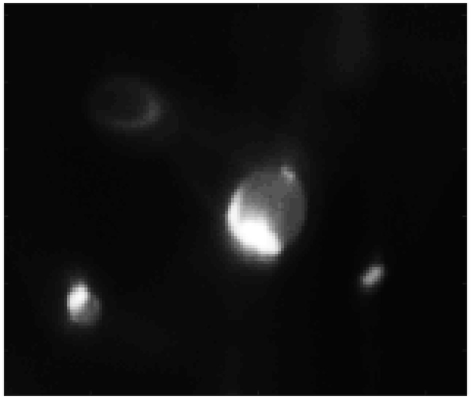
$$where\ \ R = \frac{I_2}{I_1}\frac{E_1\eta_1}{E_2\eta_2}$$

- Determine the matching pixels from DIH camera to pyrometer cameras (low intensity pixels removed)

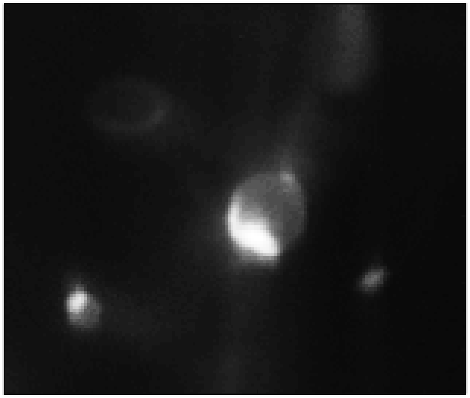
Calibration against lamp source



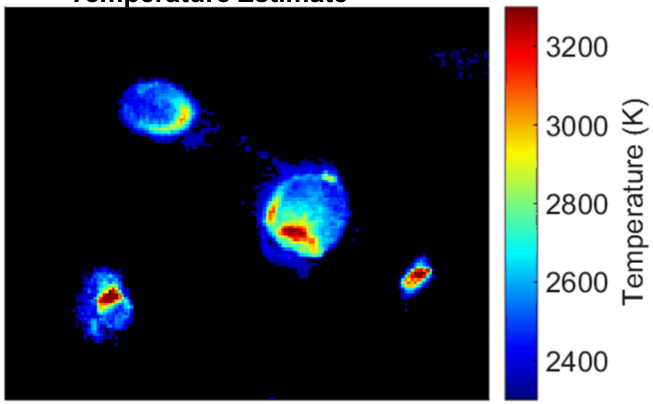
700 nm



905 nm

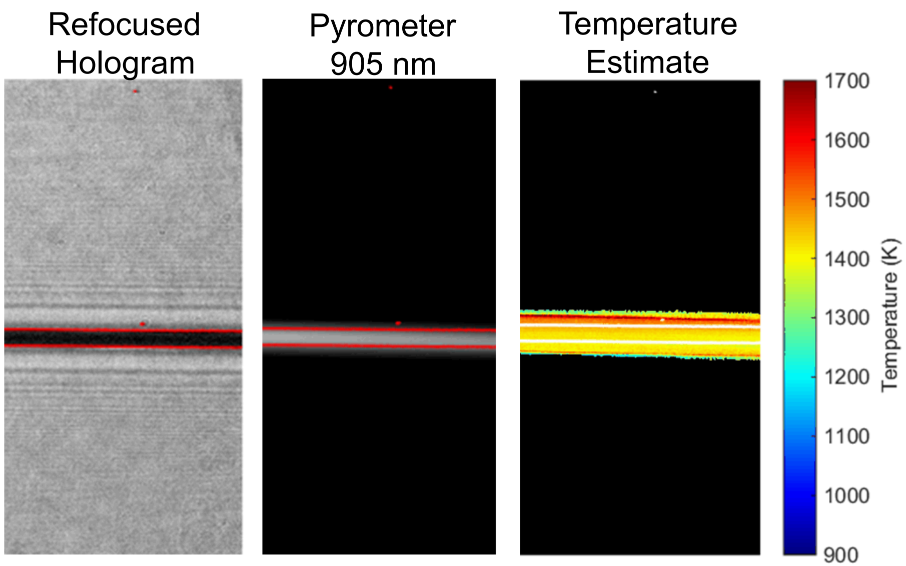


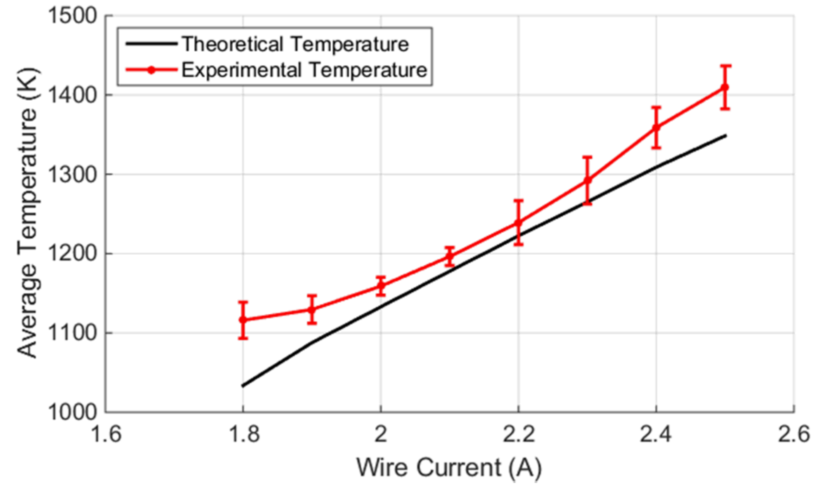
Temperature Estimate



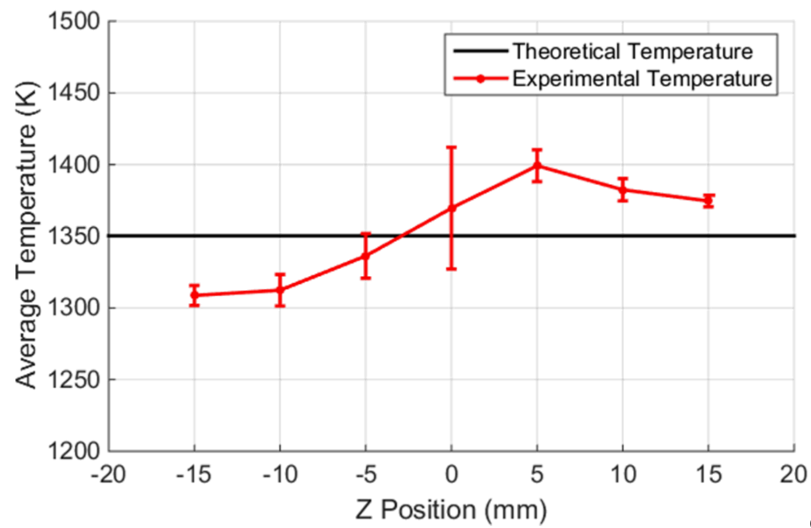
Calibration against Princeton Instruments LED source

Pyrometer Calibration

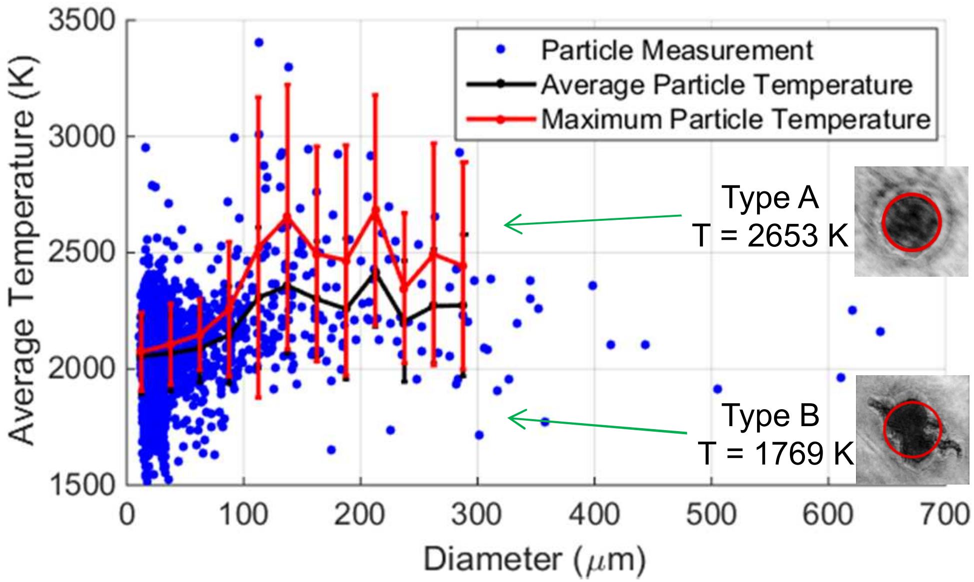


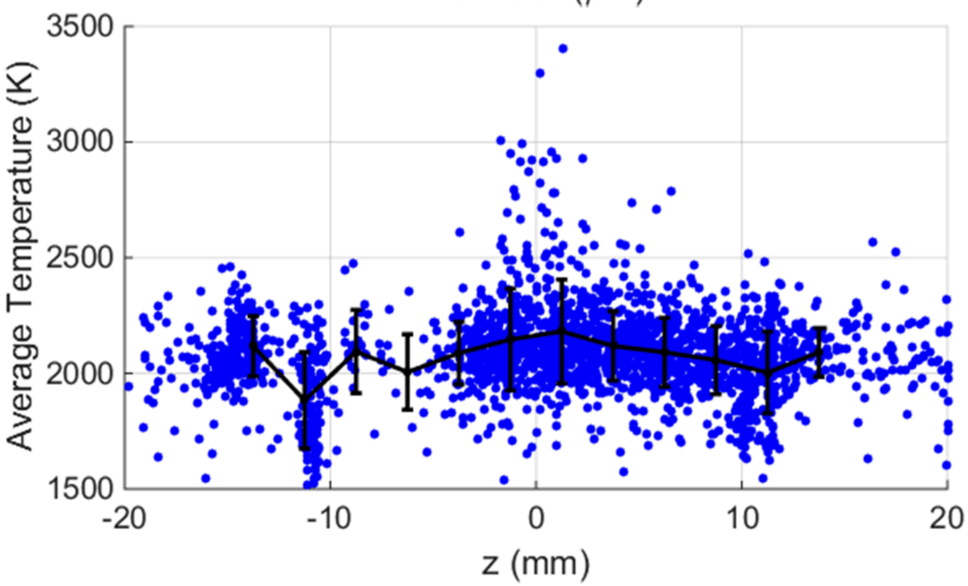


- Checked temperature calibration against a 240 µm hot nichrome wire
- Determined the effect of focus on temperature estimate
  - In-focus features have more temperature variation
  - Out-of-focus features have less variation
  - Overall temperature variation ±50 K



Measured Statistics





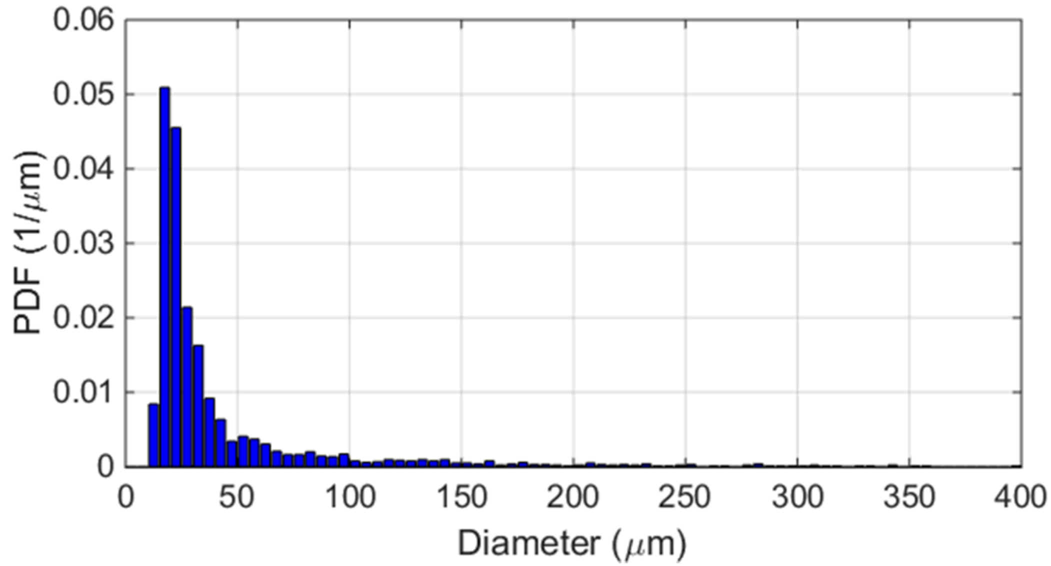
- One propellant stick burn with 2120 particles across 143 frames
- Sampled at 14 fps, each frame is uncorrelated

- Temperature of small particles approaches the temperature of the gas quickly
- Average particle temperatures are less than boiling point for Al (2792 K)
- Maximum particle temperatures less than boiling point for Al_2O_3 caps (3240 K)

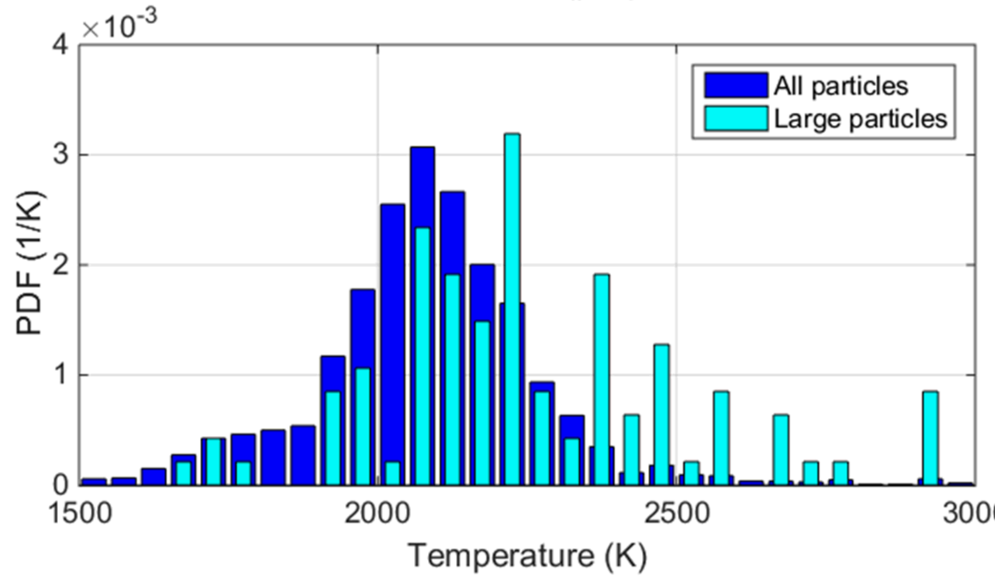
- Temperature variation near the focal point is the greatest,
  - Similar to the calibration
  - May be evidence of hotter particles in the center of the flame

Measured Statistics

- The majority of the particles are small
- D_{10} = 43.0 µm
  (mean diameter)
- D_{32} = 249 µm
  (Sauter or surface area weighted)
- D_{43} = 377 µm
  (volume weighted)

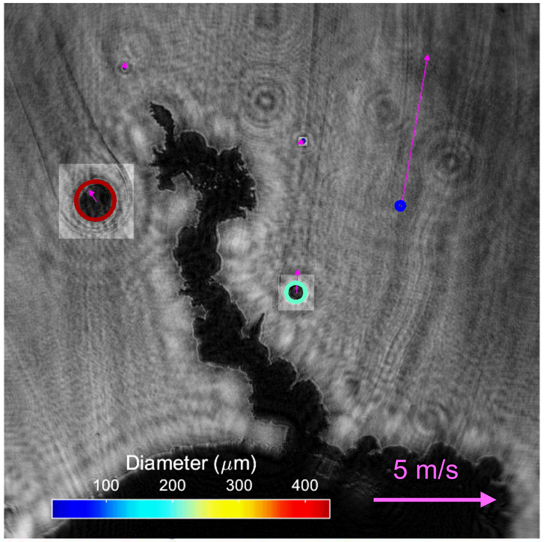


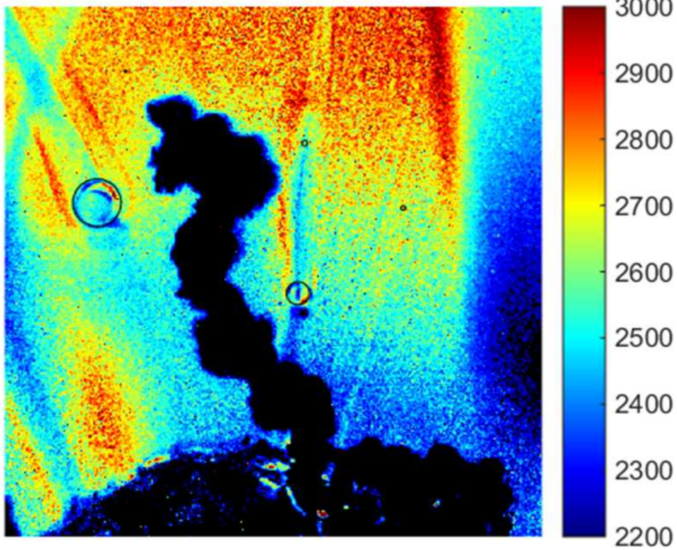
- Particle temperatures are a complex mixture of particles in different stages of combustion
- Since most of the particles measured are small, we expect average temperatures to be similar to gas temperatures
- For all particles
  T_{ave} = 2084 ±189 K
- For large particles (>150 µm)
  T_{ave}= 2131 ± 256 K
- Similar to average gas temperatures measured with CARS



Conclusions and Future Work

- Demonstrated simultaneous DIH and Two-Color Pyrometer measurements of aluminized ammonium perchlorate propellant sticks
  - Position
  - Size
  - Temperature
- Sources of error and bias
  - Temperature calibration accuracy
  - Camera readout smear for short exposures
  - Gray body assumption
  - Overlap of particles and soot at different temperatures
- Future work
  - Additional propellant stick burns for better statistics
  - Velocity statistics to correct probability distributions

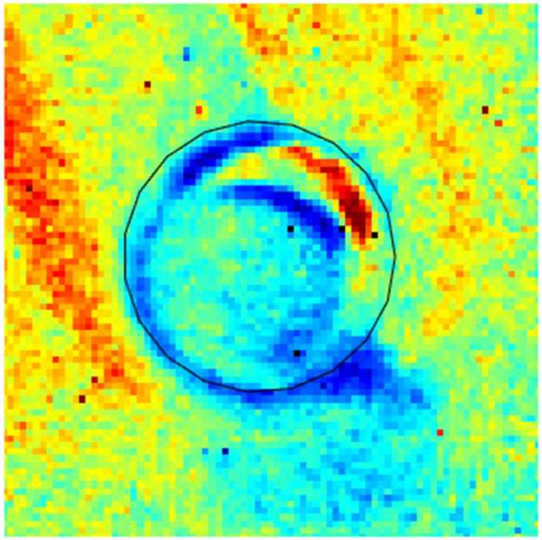




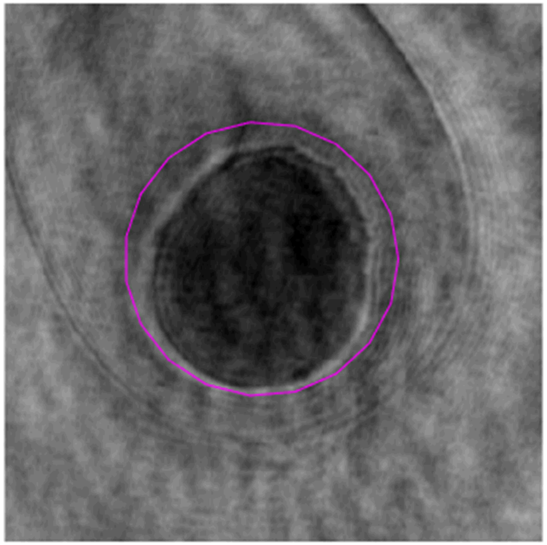
Acknowledgements

- The Weapons Systems Engineering Assessment Technology program
- The Laboratory Directed Research and Development program
- Howard Lee Stauffacher for his work with the propellant igniter system
- Thomas W. Grasser for his work with the optical system construction

Temperature Estimate



Refocused Hologram



QUESTIONS?

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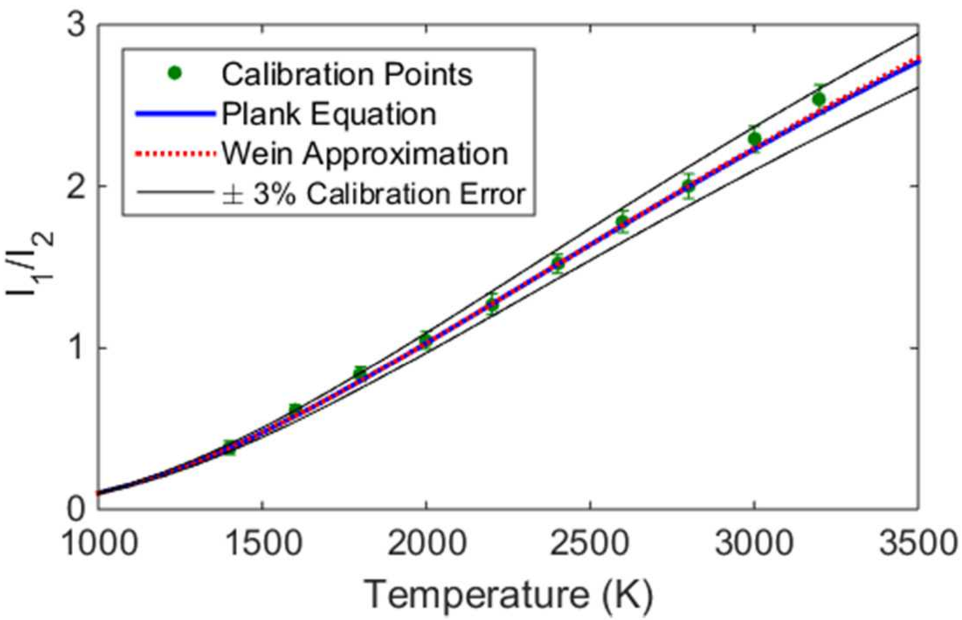
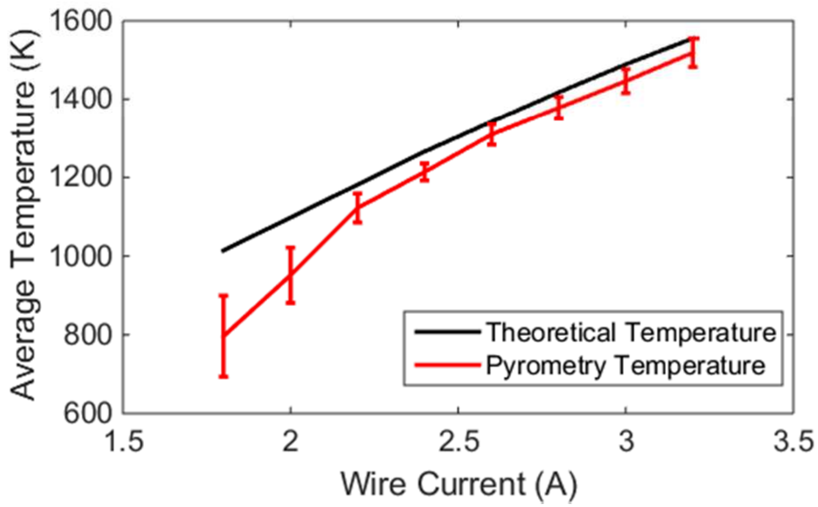
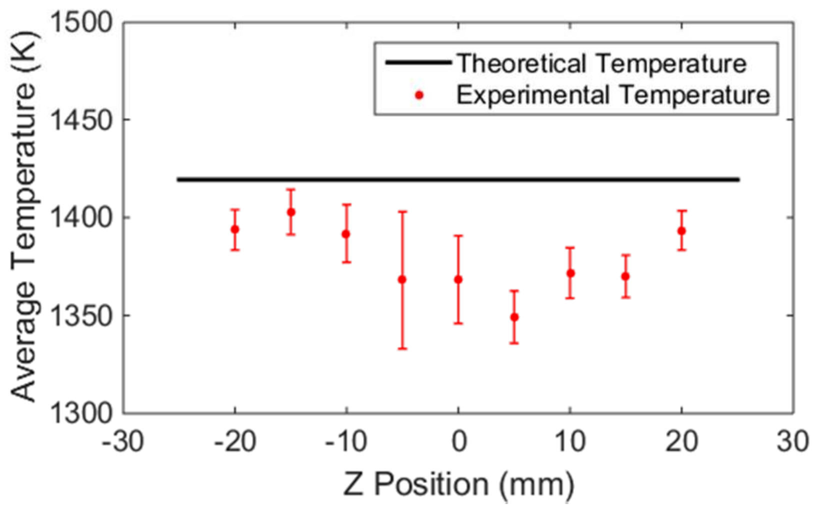
BACKUP SLIDES

Black Body Calibration

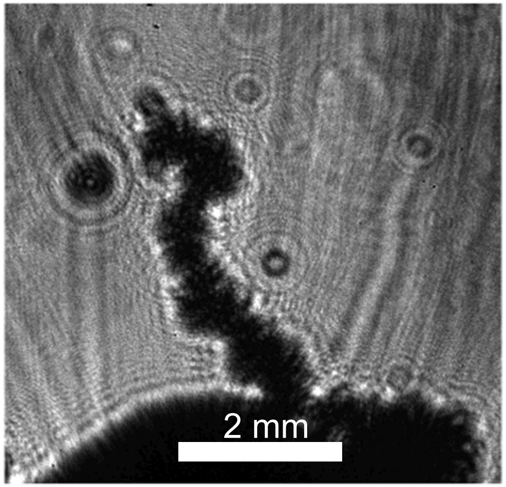




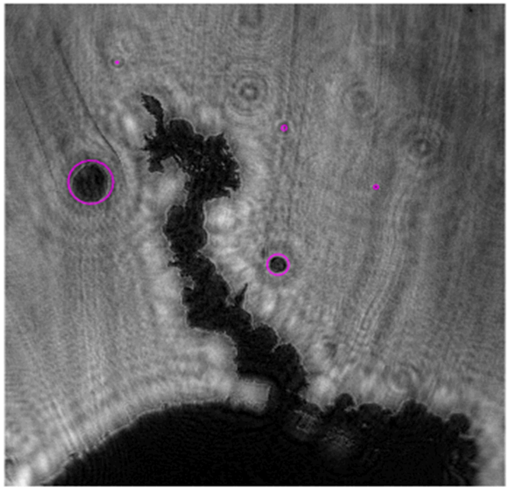


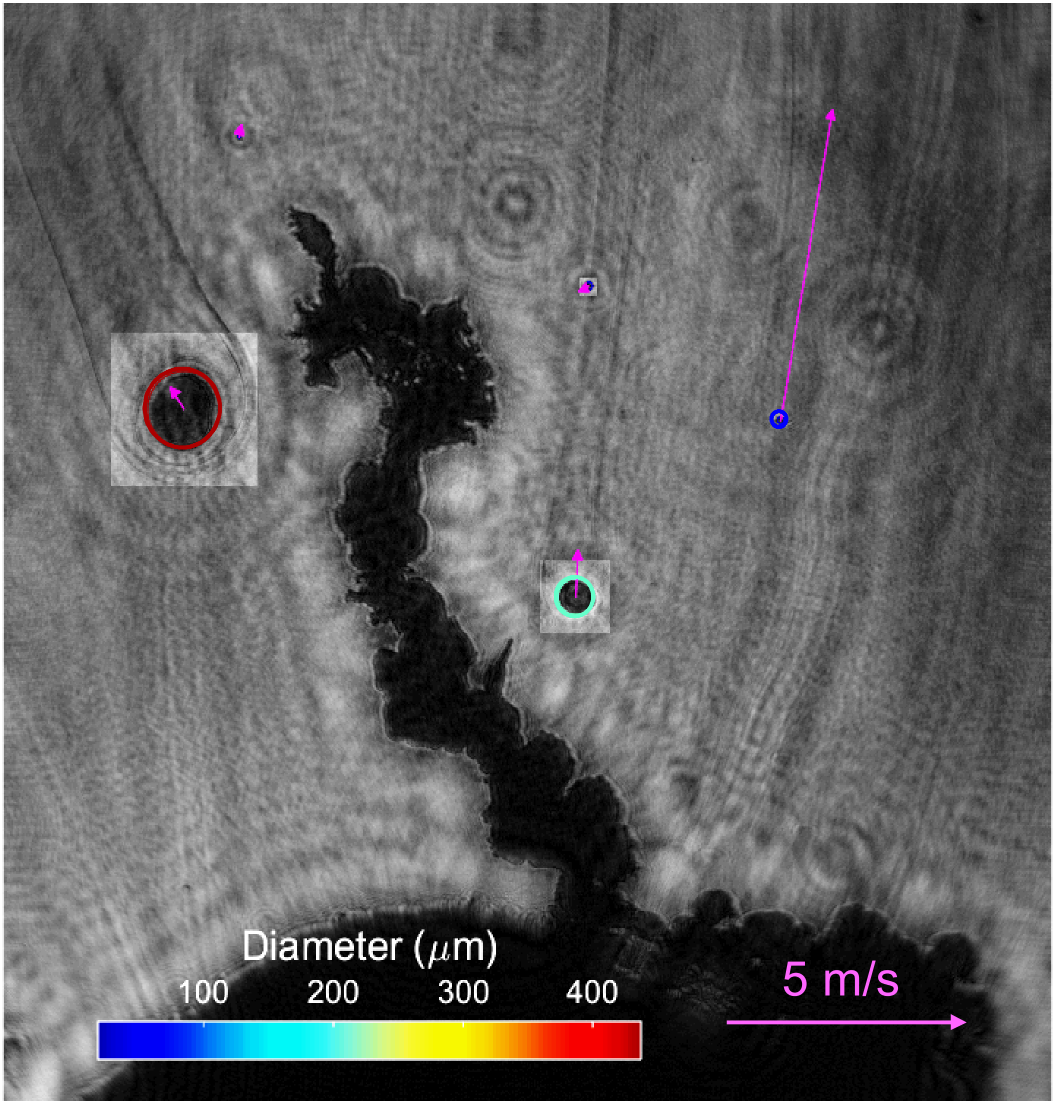
Velocity Measurement

Raw Hologram

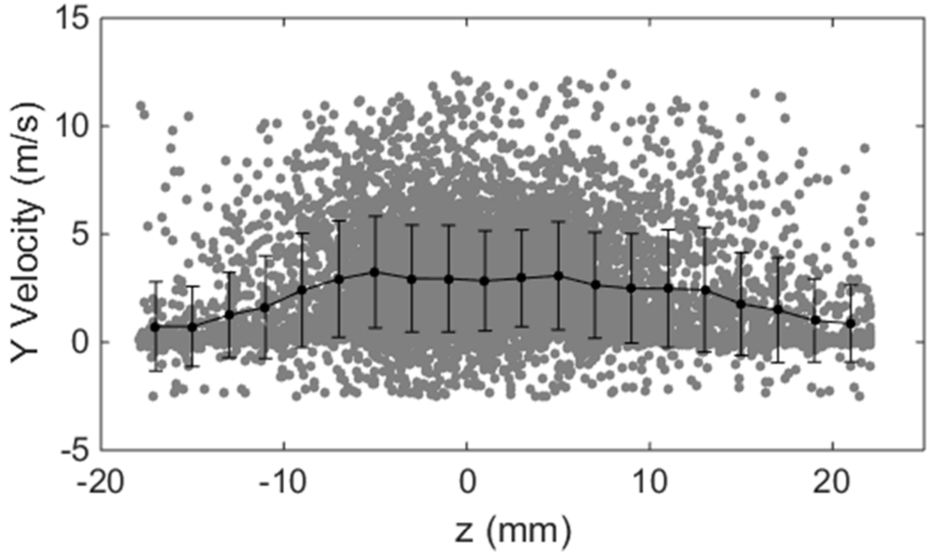


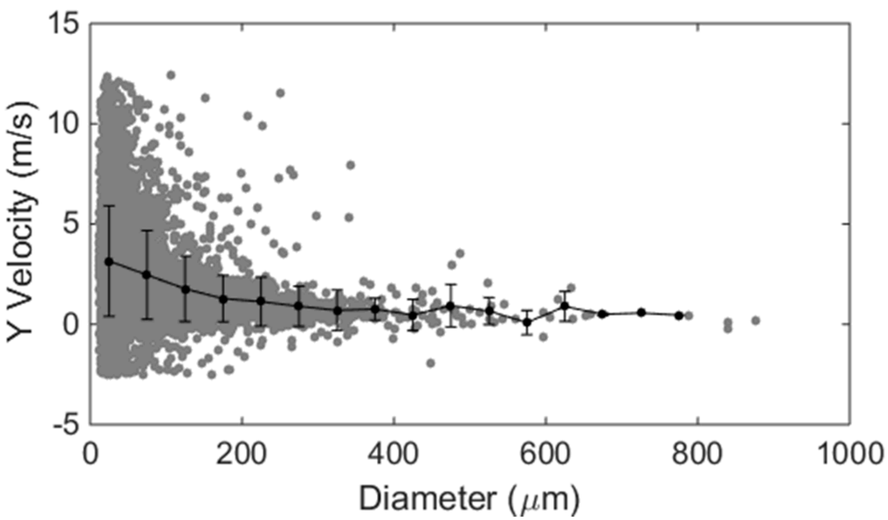
Refocused Hologram

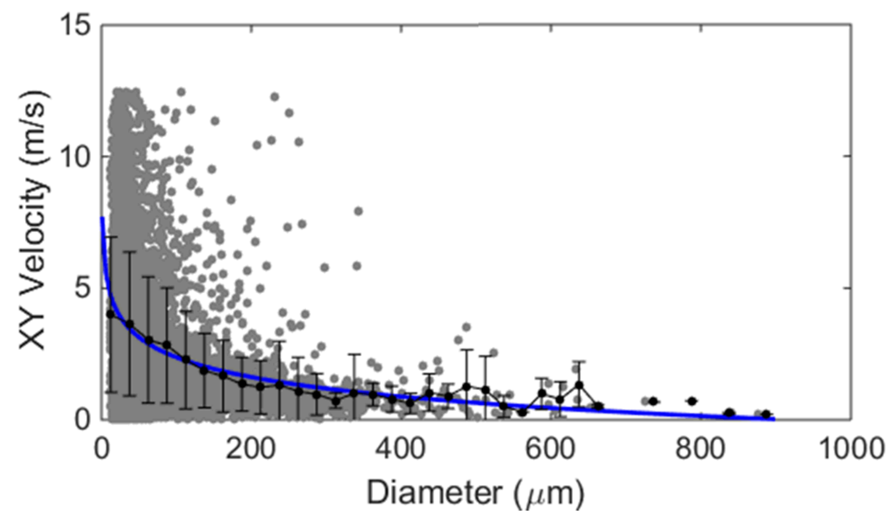




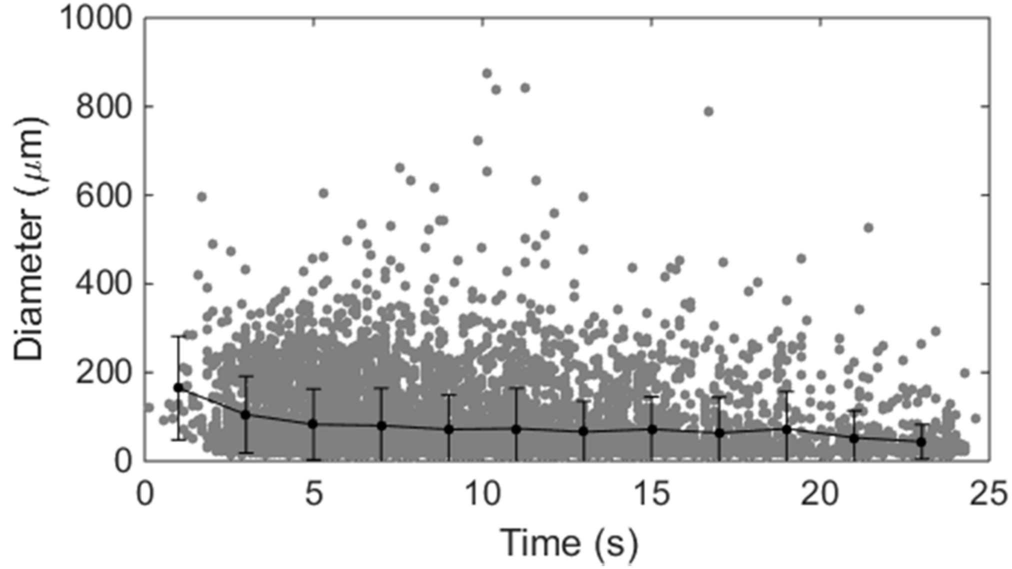
Velocity Measurement

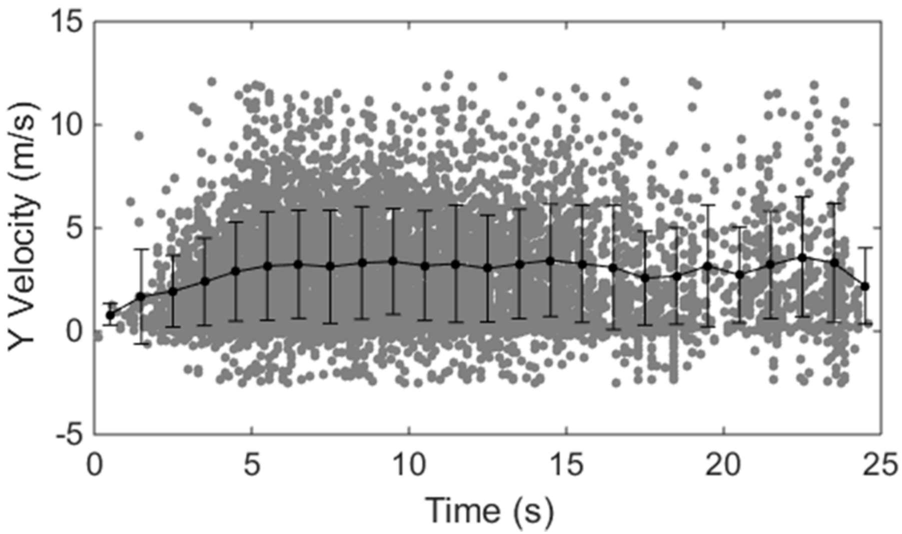


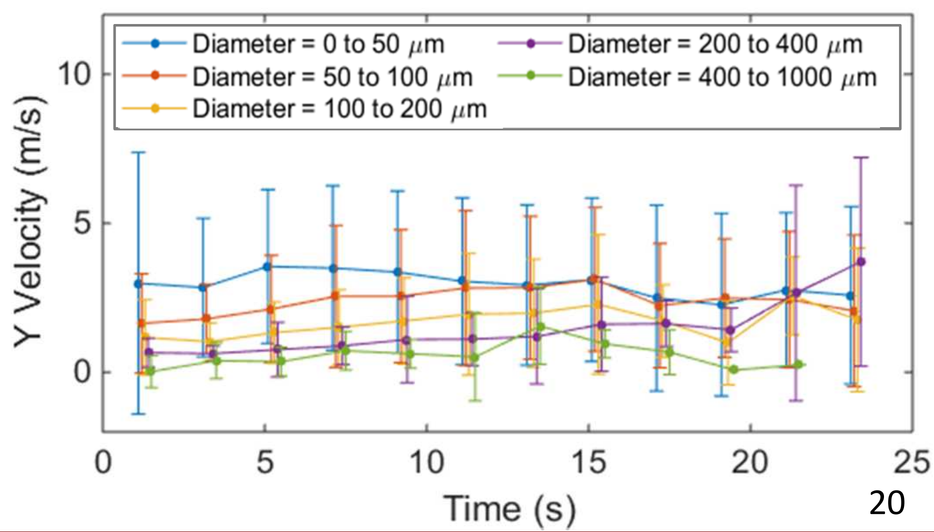




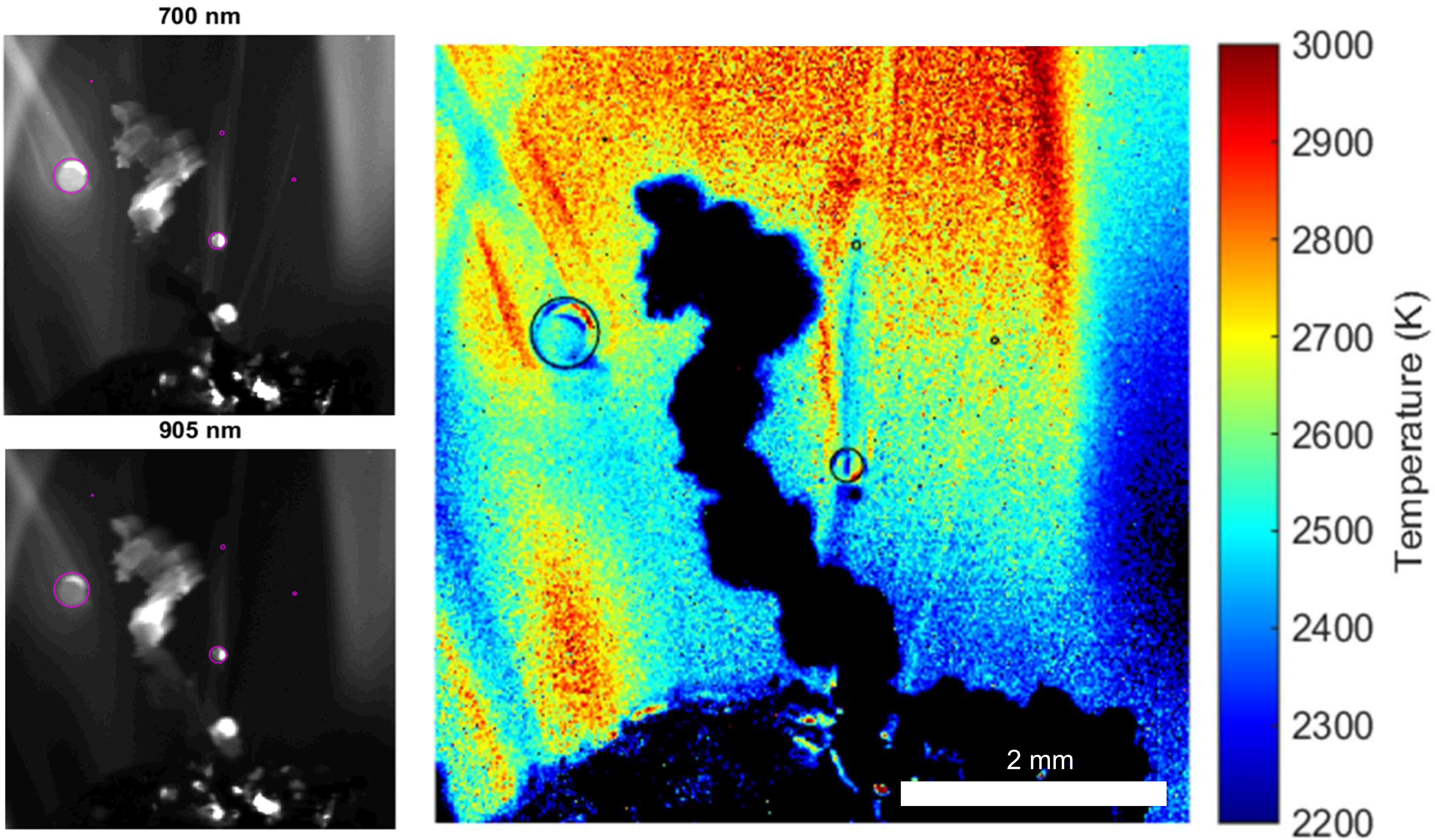
Time Evolution







Temperature Measurement



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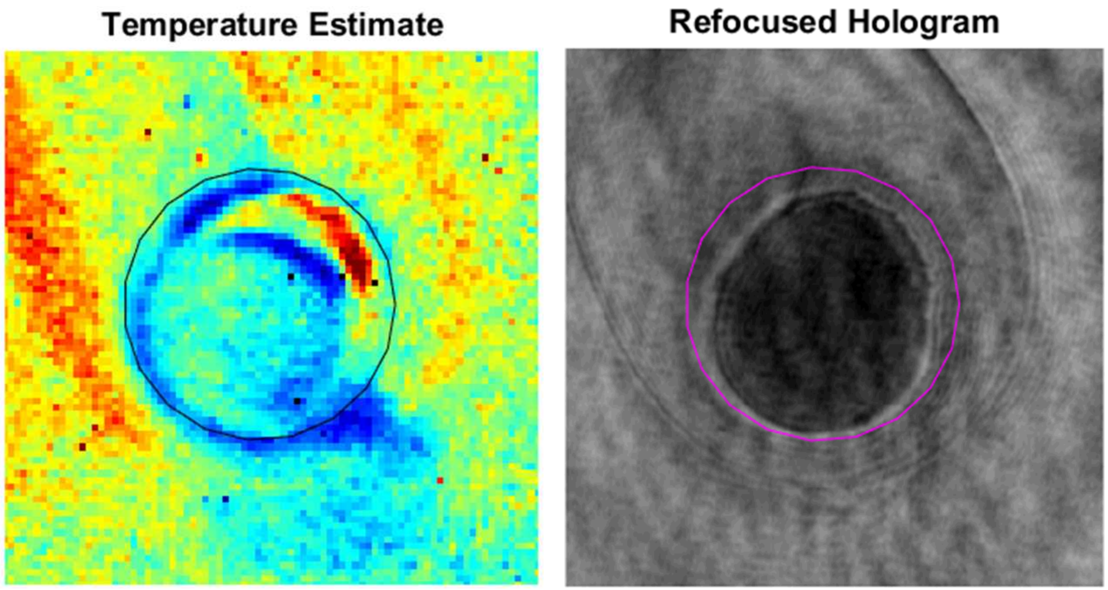
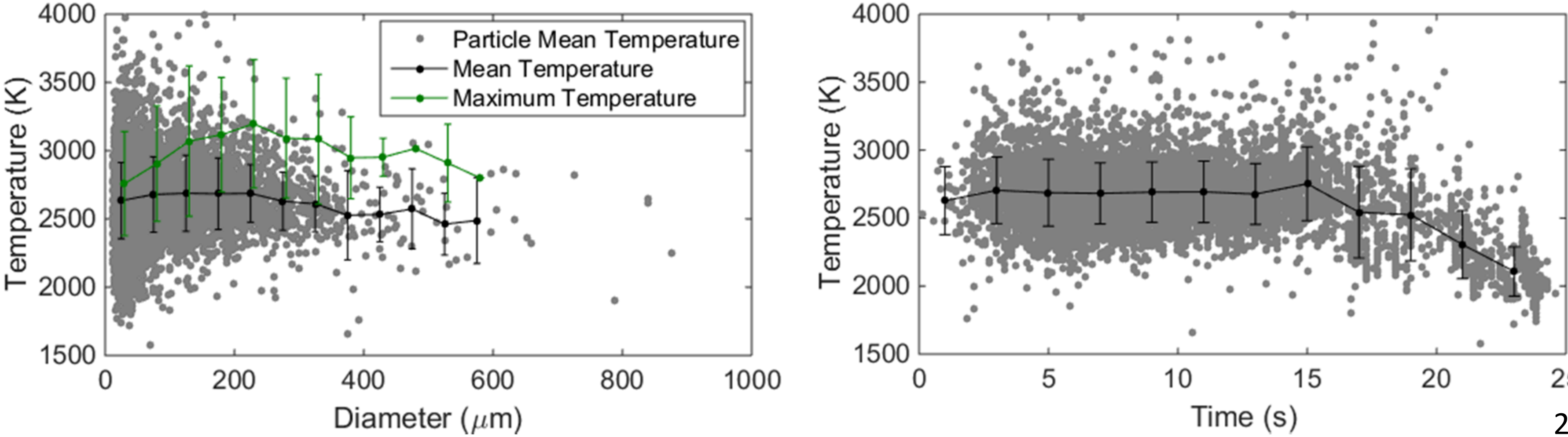
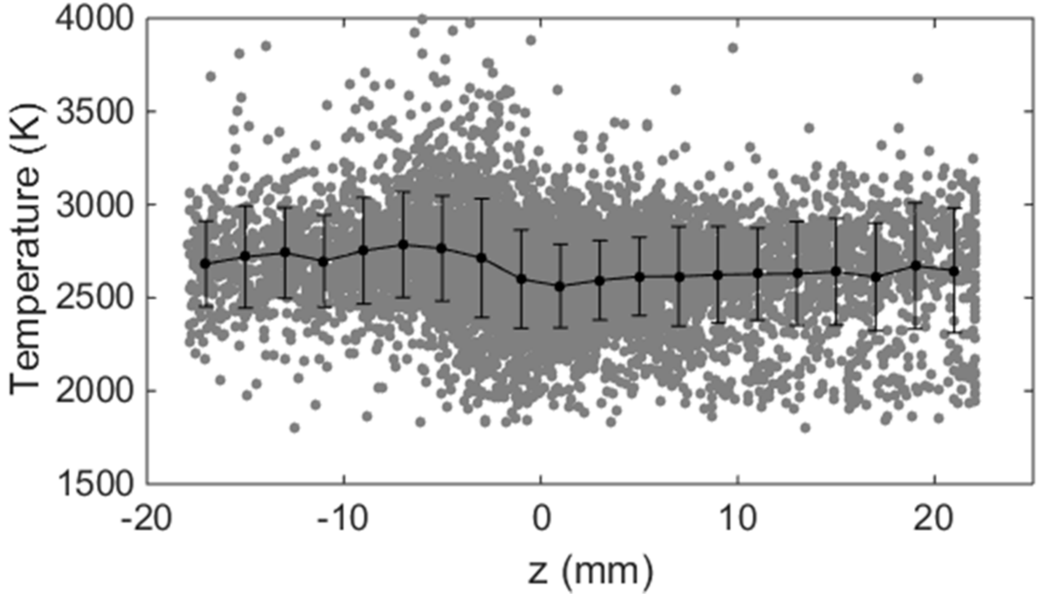
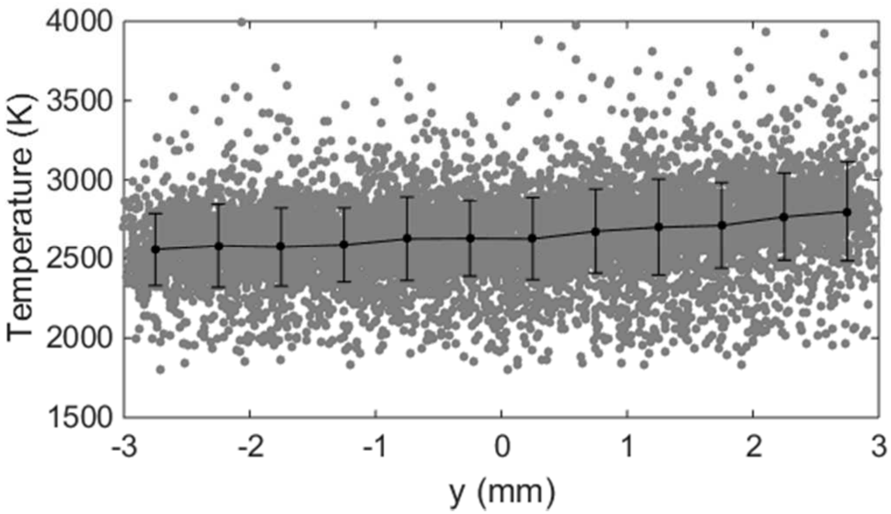
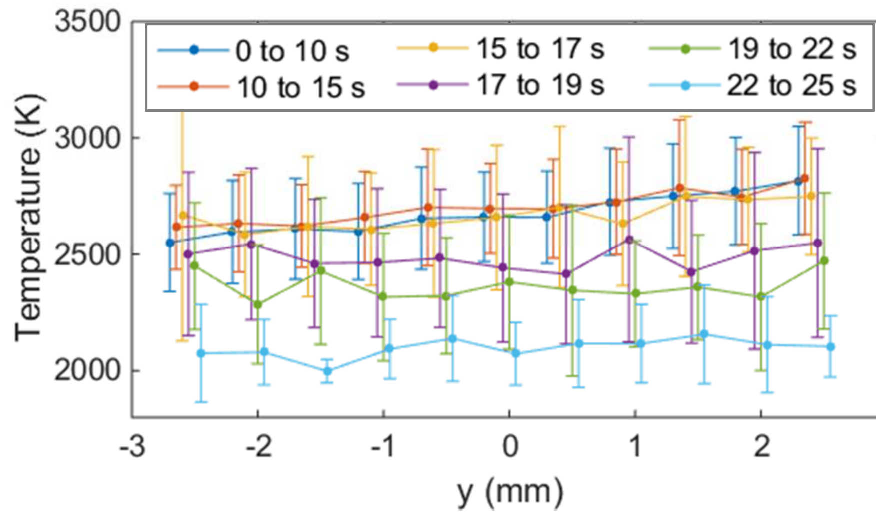




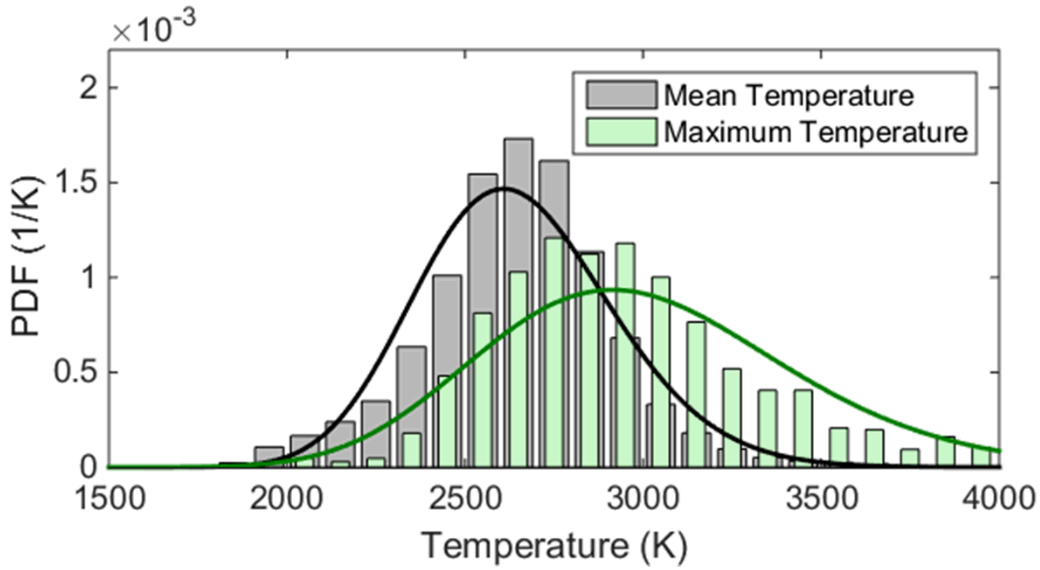
Temperature Measurement

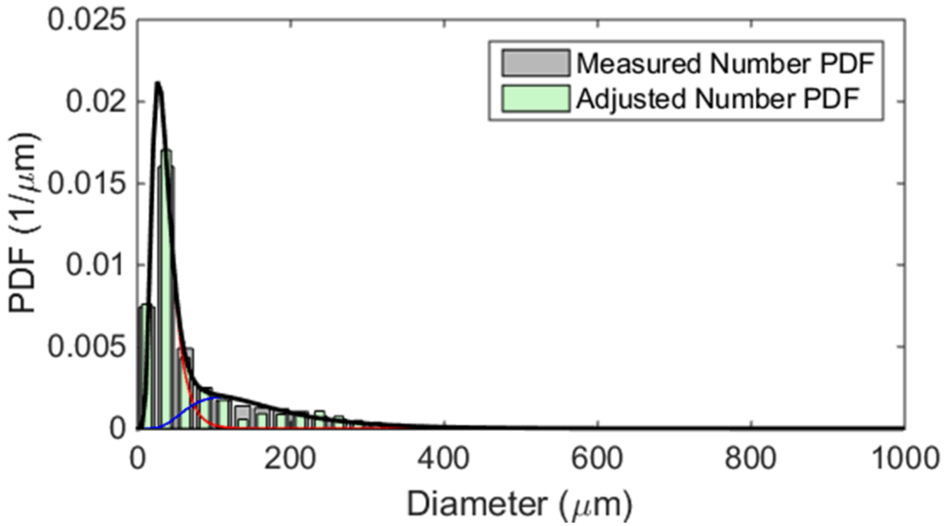


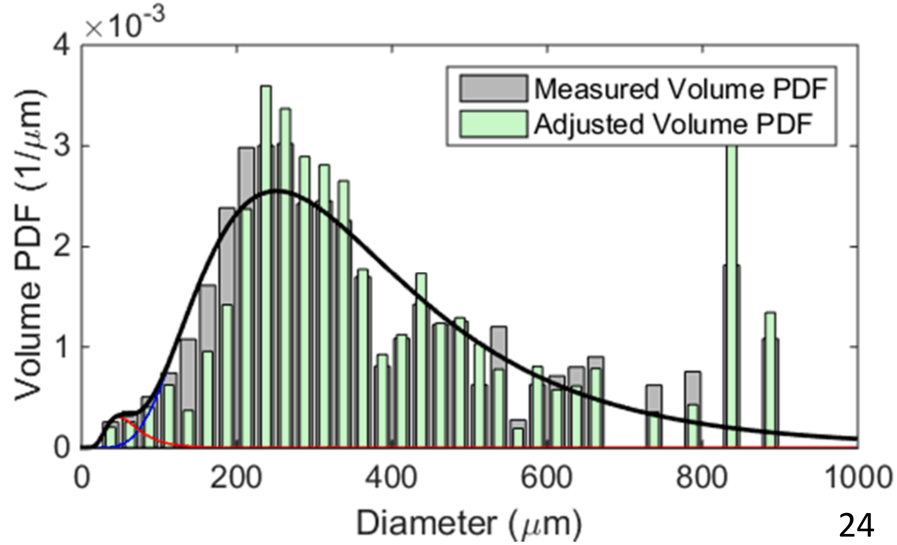




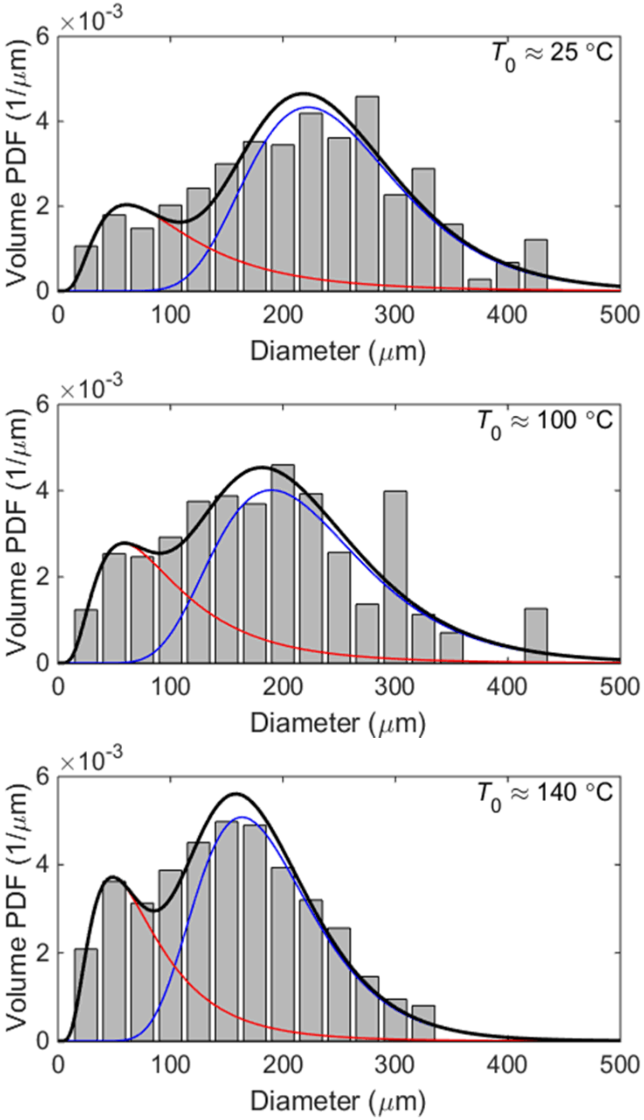
Particle Statistics







Initial Propellant Temperature



T_0 (°C)	N	D_{10} (μm)	D_{32} (μm)	D_{43} (μm)	MMD (μm)
25	17496	37.9	150.7	217.6	220.5
100	6890	39.0	127.4	187.6	185.7
140	15346	35.2	104.5	153.8	151.6

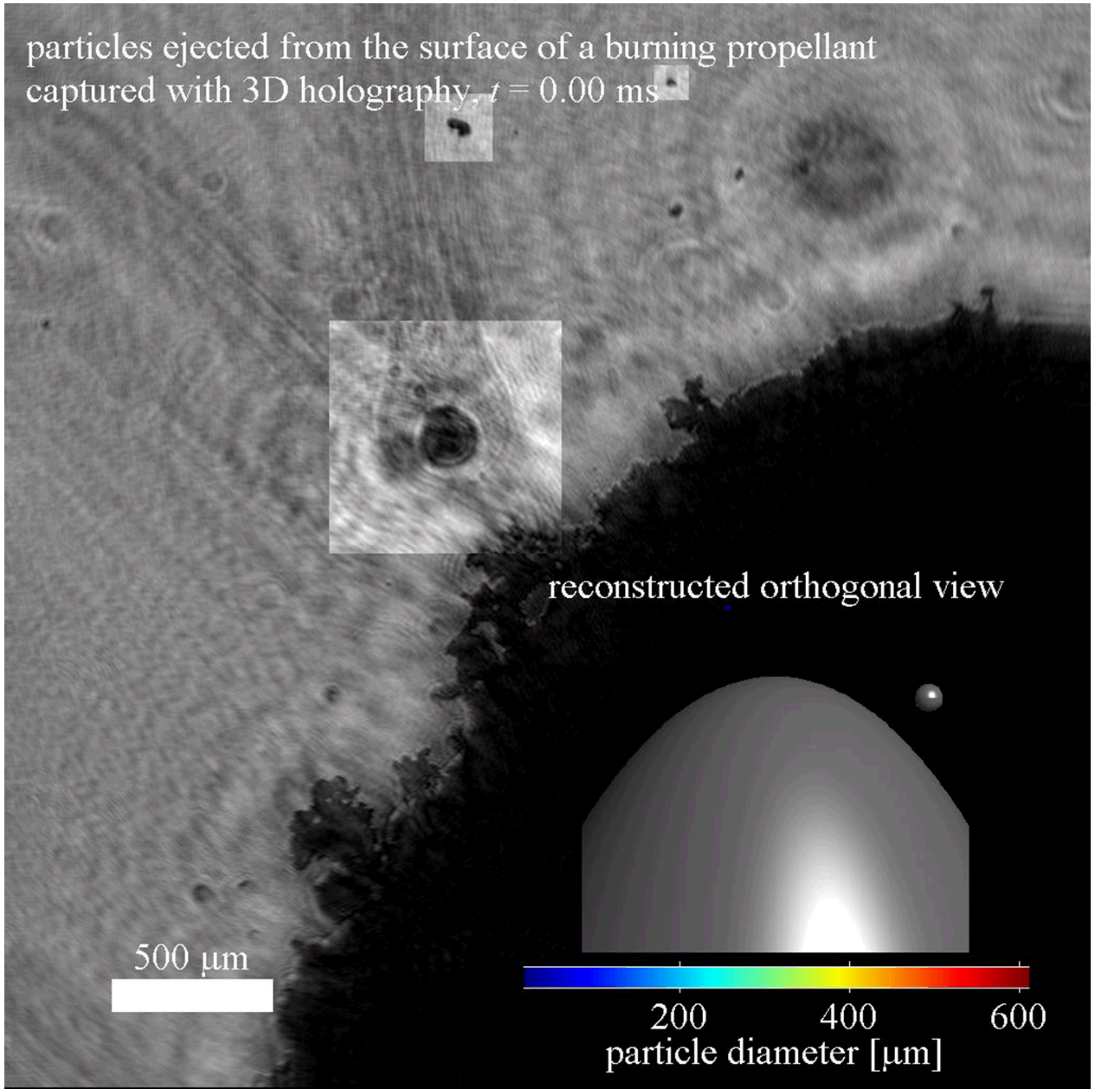
Bi-modal log-normal fits

$$f(d) = \frac{1-w}{d\sigma_a\sqrt{2\pi}} e^{-\frac{(\ln d-\mu_a)^2}{2\sigma_a^2}} + \frac{w}{d\sigma_b\sqrt{2\pi}} e^{-\frac{(\ln d-\mu_b)^2}{2\sigma_b^2}}$$

T_0 (°C)	w	μ_a (ln[μm])	σ_a (ln[μm])	μ_b (ln[μm])	σ_b (ln[μm])
25	0.74	4.56	0.67	5.49	0.29
100	0.69	4.47	0.64	5.36	0.34
140	0.67	4.25	0.61	5.19	0.31

As the initial propellant stick temperature increases, the minimum size of agglomerated particle decreases and the weight fraction of larger particles decreases

High Speed Video



Two-Color Pyrometry

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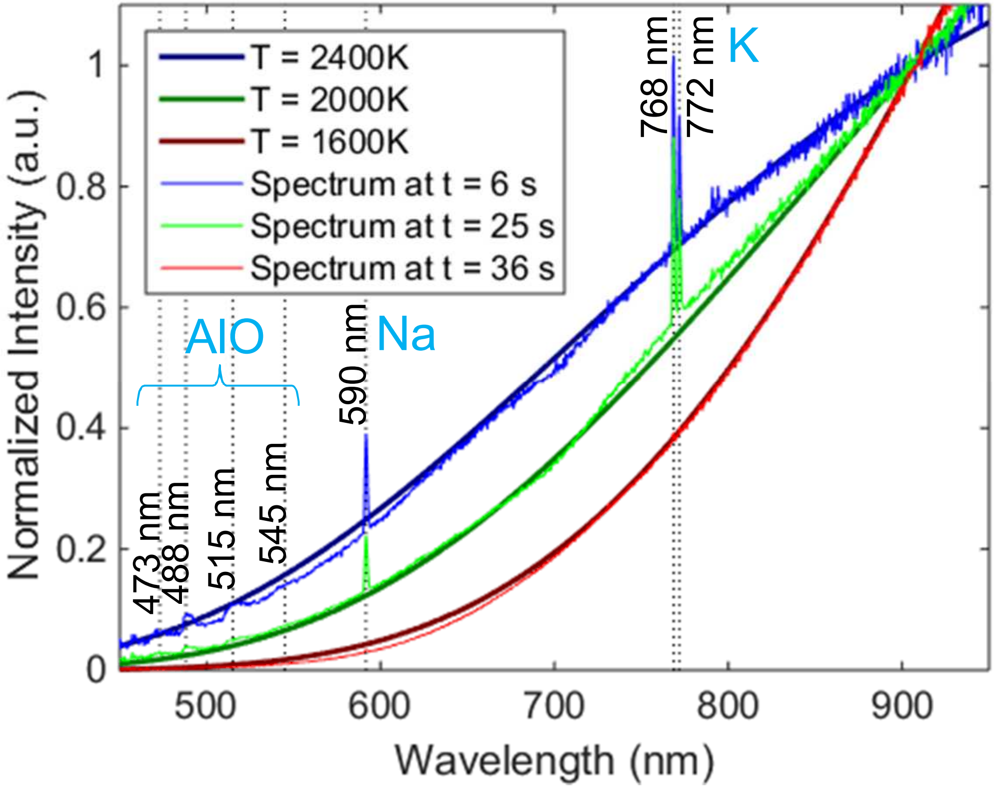

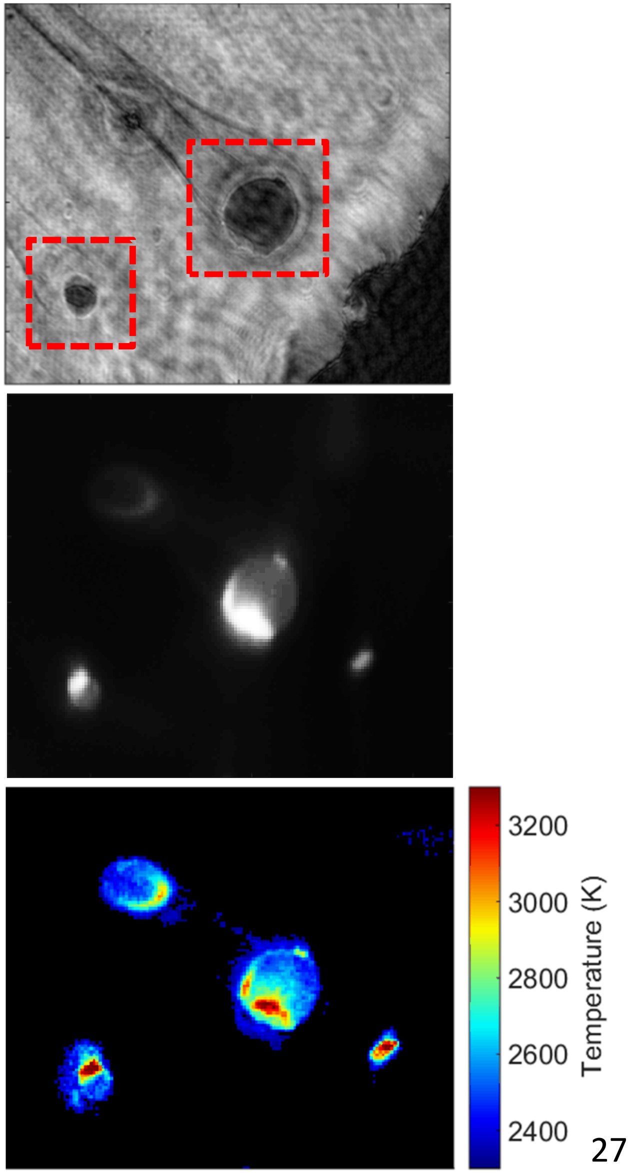

Equations

Diffraction Integral Equation

$$E(x,y,z) = \frac{1}{\lambda}\iint E(\xi,\eta,z=0)\frac{e^{-jkr}}{r}d\xi d\eta \quad \text{where: } r = \sqrt{(\xi - x)^2 + (\eta - y)^2 + z^2}$$

Two-Color Pyrometer Equation using Wein's Approximation

$$T = \left[\frac{k}{hc}\frac{\lambda_1\lambda_2}{\lambda_2 - \lambda_1}\left(\ln(R) - 5\ln\left(\frac{\lambda_1}{\lambda_2}\right)\right)\right]^{-1}$$

$$where \;\; R = \frac{I_2}{I_1}\frac{E_1\eta_1}{E_2\eta_2}$$