Diagnostic Applications of Macrophotography and High-Speed Imaging in Combustion Particle and Spray Droplet Characterization

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Background

Characterizing the distributions of droplets and particles within combustive fuel systems is imperative to improving system uniformity, efficiency, and performance. For sprays and solid propellant systems, both the overall droplet/particle size distribution and size-location relationship help dictate system effectiveness. Conventional methods of droplet and particle characterization utilize advanced technologies (e.g., laser diffraction) to accommodate the high-speed, macro-scale nature of sprays and combustion. While highly accurate, such advanced technologies can be significant financial investments with minimal functional versatility. Thus, this project explores a versatile method of characterizing droplet and particle distribution by combining the existing technologies of high-speed imaging, macrophotography, and software-based data analysis. In theory, a system comprised of these components could (1) clearly view the macroscopic droplets/particles during spray/combustion, (2) convert the brief events into thousands of frames, and (3) analyze each frame individually to determine the presence, size, and subsequent distribution of all visible droplets/particles. The testing procedure covered here consists of using the proposed system to analyze a flat-fan spray, full-cone spray, and solid propellant combustion. The variety of testing conditions functions as a measure of the system's versatility.

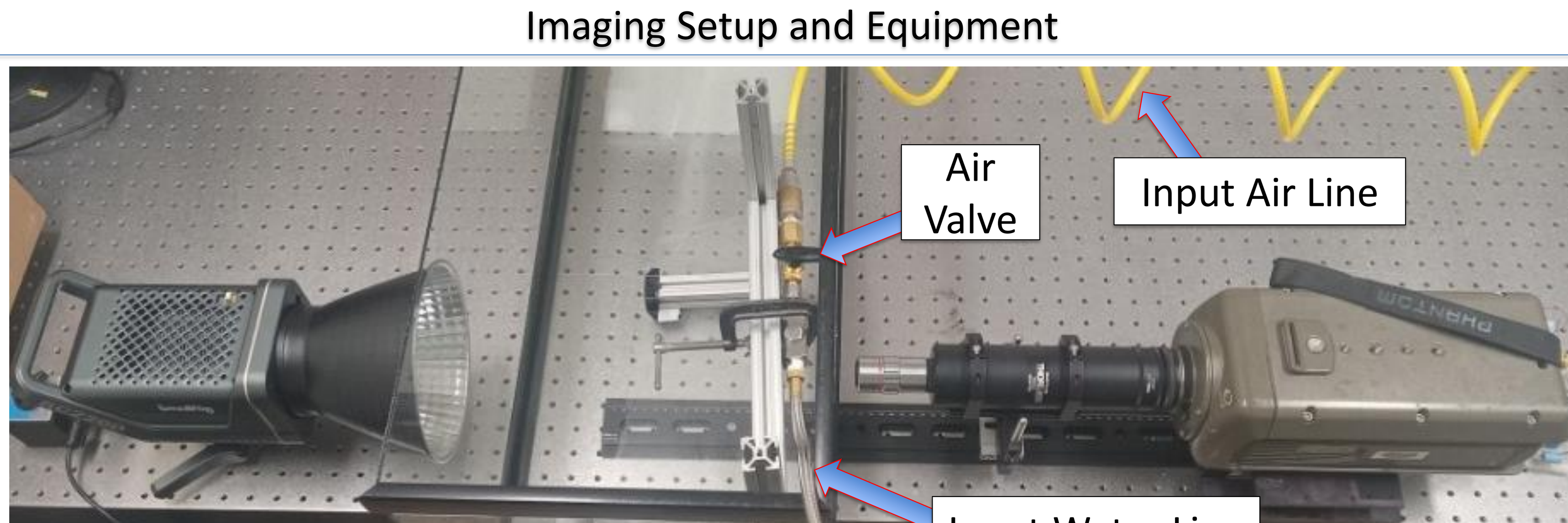
Objectives

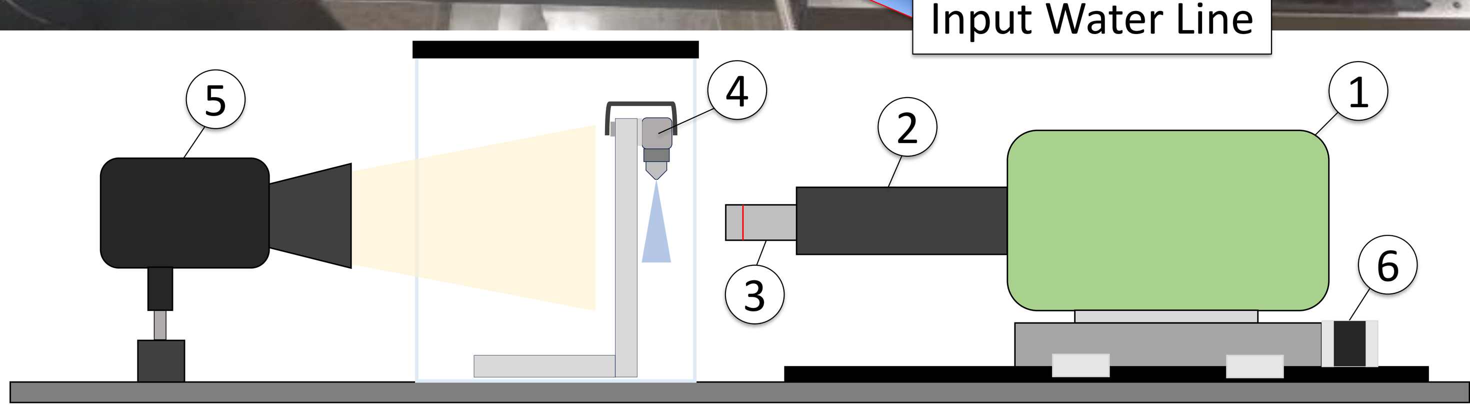
- Obtain clear imaging of droplets with diameters in the 10-100 µm range during a spray.
- Obtain clear imaging of solid propellant particles throughout the combustion process.
- Observe consistent droplet diameter distribution for all test conditions. Ideally, each test will produce a "normal" or Gaussian distribution defined by a mean and standard deviation.
- Determine a size-location relationship in addition to overall size distribution by analyzing different planes and plane sections of the same spray/propellant.
- Achieve repeatability of an image analysis program across varying spray/combustion videos. This will prove the system is useful for, but not limited to the conditions of this research.
- Demonstrate spray droplet characterization consistent with existing, alternative spray diagnostic systems (e.g., Malvern Spraytec, which utilizes laser diffraction).

Approach

For this approach it is assumed that the droplet size distribution throughout an entire uniform spray can be accurately characterized by the distribution within a single plane of the spray over time. Ideally, with enough identified droplets (i.e., a large enough sample size), it is assumed that the characteristics of the observed plane are representative of the entire spray volume.

Imaging Setup and Equipment



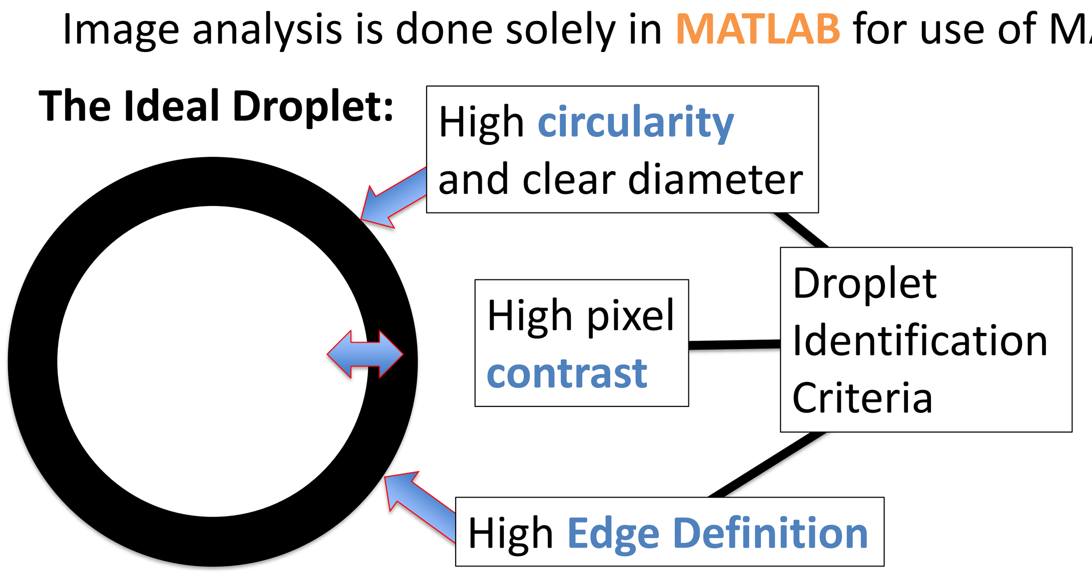


1. Phantom V310 high-speed camera running at 3200 fps and 1 µs exposure
2. Series of image plane extensions and lenses that collimate the light prior to sensing
3. Mitutoyo M-Plan Apo microscope objective (5x/10x) needed for magnification
4. Spray assembly (flat/cone) that produces droplets in the desired size range
5. Variable-intensity light that allows for brightened images at the 1 µs exposures
6. Motor-controlled stage used to vary the camera's linear position with 1 µm resolution

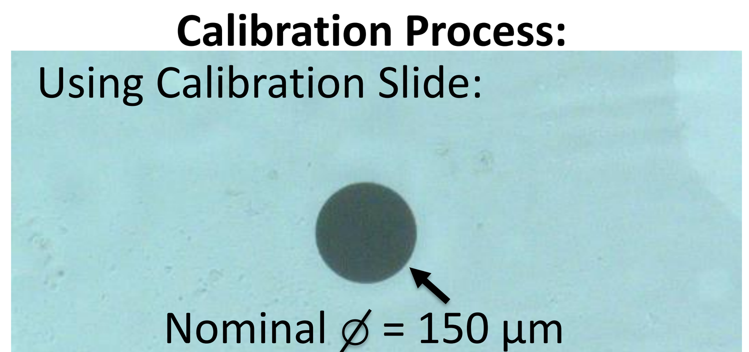
Operation: The live video feed and linear stage are used to achieve proper focus. Air and water inputs are then separately introduced until a uniform spray is manually observed and captured.

Post-Capture Image Analysis and Droplet Characterization

Image analysis is done solely in MATLAB for use of MATLAB's Image Processing Toolbox.

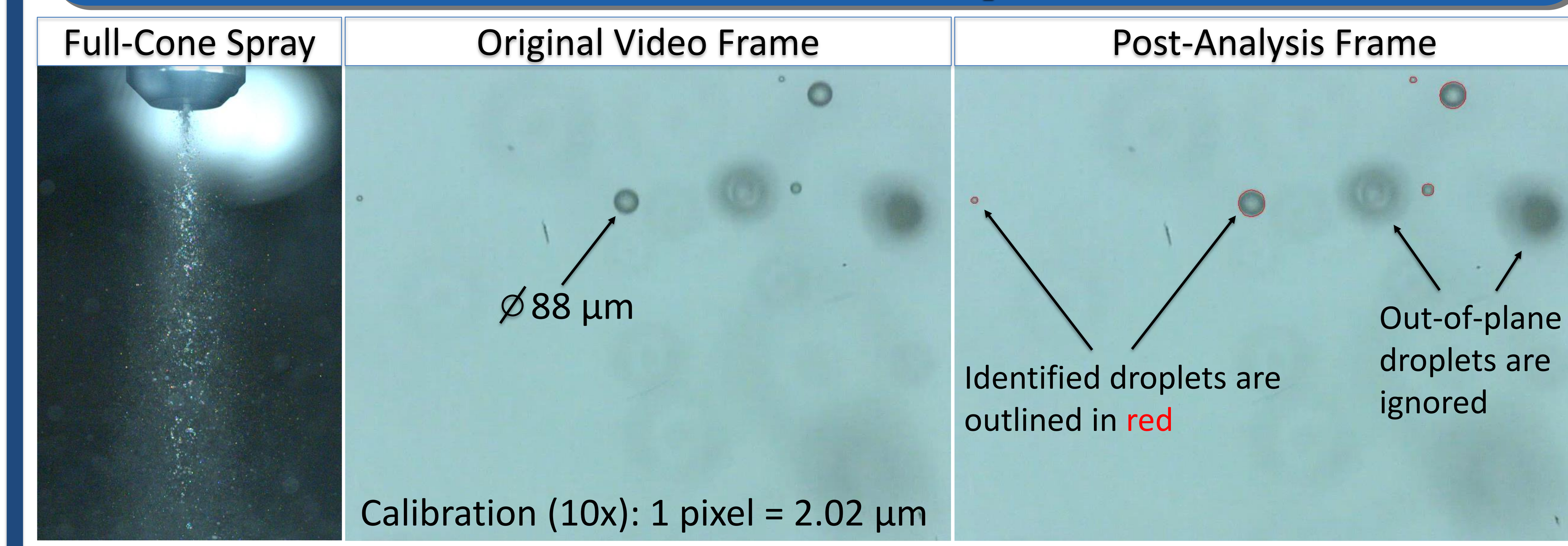


Calibration Process:

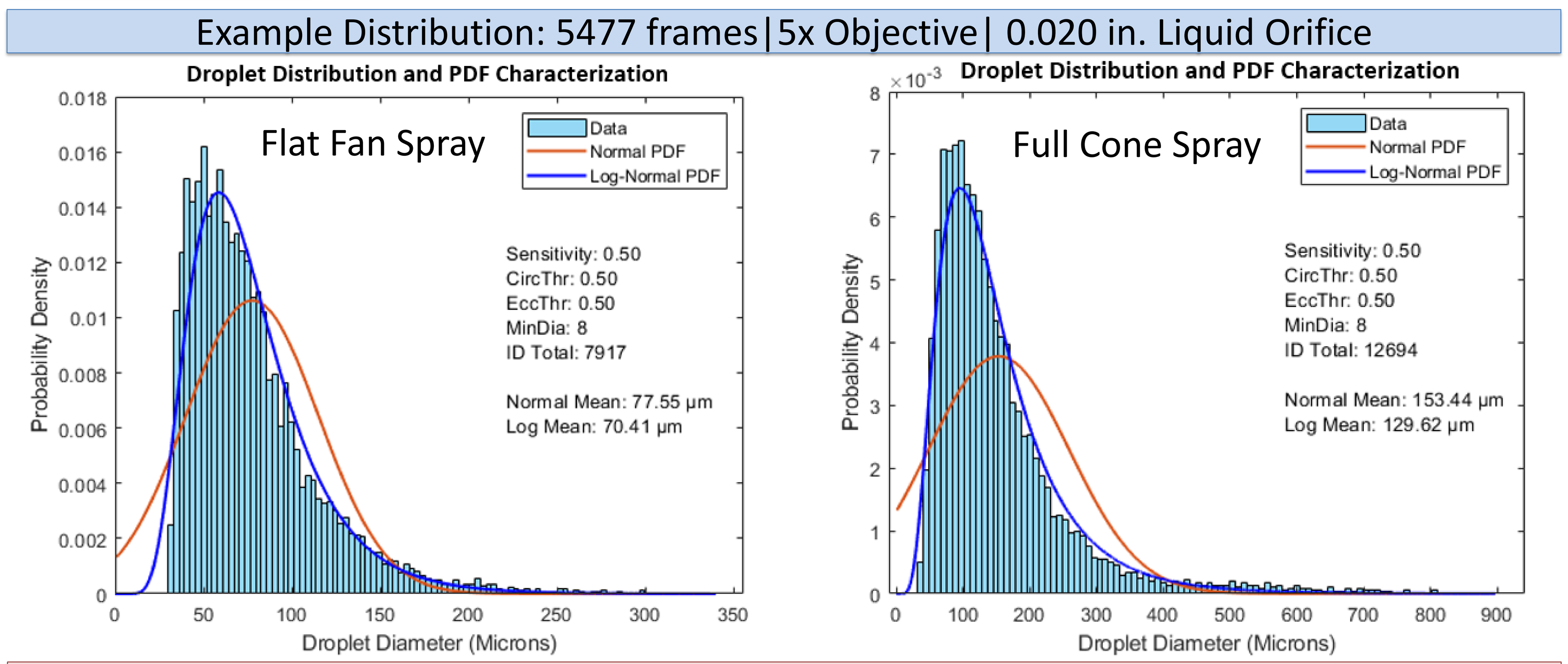


5x Objective:	4.04 µm/pixel
10x Objective:	2.02 µm/pixel

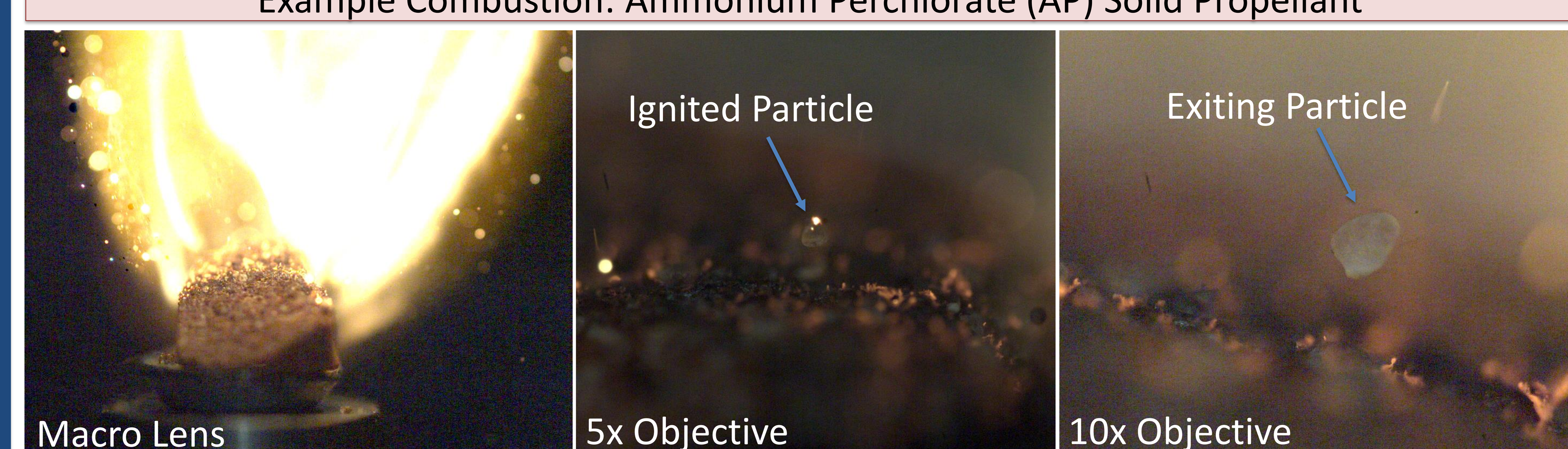
Results / Analysis



Example Distribution: 5477 frames | 5x Objective | 0.020 in. Liquid Orifice



Example Combustion: Ammonium Perchlorate (AP) Solid Propellant



Conclusions

- Visual observations indicate ≈ 85% accuracy in droplet identification. Error persists with the intermittent exclusion of "valid" droplets and inclusion of partial or out-of-plane droplets.
- Results thus far support spray droplet characterization via the lognormal distribution, rather than the normal distribution. This finding is supported by existing droplet characterization literature and therefore helps validate the methodology discussed herein.
- Inconsistent lighting and spray conditions can require unique adjustments to the analysis program for each video. This suggests that upgraded lighting, input regulators, and more versatile droplet identification criteria are necessary additions for future work.
- Overall, the system demonstrated its expected versatility with the ability to adjust lenses, imaging settings, and analysis code. The image analysis code will most significantly influence distributions and characterizations in future tests.

Future Research

- Expand image analysis to combustion videos (recently obtained) and improve spray analysis by exploring alternative and more comprehensive droplet identification methodologies
- Increase lighting consistency and further minimize image exposure (< 1 µs). This may be done by implementing an integrated lighting system that can adjust to imaging settings.
- Define input conditions by regulating input flow rates and/or pressures. This will allow for a measure of analysis repeatability and the concatenation of identical-input test results.
- Analyze sprays with larger nominal droplet diameters (e.g., 200-500 µm) to validate the 10-100 µm distributions produced by the current image analysis program.
- Compare size distributions for various planes and plane sections of the same spray to quantify a size-location relationship for given input conditions.
- Increase available video RAM to allow for longer videos and greater data sample sizes.

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