Atmospheric, non-combusting droplet sizing and spray imaging results from a non-proprietary aero gas turbine engine pressure swirl atomizer using shadowgraphy and planar laser scatter

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Motivation and Background

- An Aero-Spray Working Group with members from NASA, Argonne National Laboratory (ANL) and several aero-engine manufacturers formed in 2020 to create a detailed database of fuel atomization characteristics internal and near fuel-nozzle exit using the x-ray data from ANL's Advance Photon Source (APS) and high-fidelity simulations.
- Atomization of liquid fuel plays one key factor in fuel-air mixing and can affect emissions and operability. Improved predictive tools for atomization can reduce design time and costs.
- Non-proprietary injectors including pressure-swirl, jet-in-crossflow and prefilming atomization for low and high temperature and pressure conditions are being designed and fabricated by Woodward FST.
- Phase I injectors designed for 1 atm and room temperature air conditions are being tested in APS to provide internal and near-nozzle x-ray data on fuel atomization with existing APS capabilities.
- Phase II and III injectors are being designed and are targeting air pressures and temperatures up to 60 atm and 1300 F.
- This presentation focuses on droplet sizing and spray quality downstream of the dome exit of the Phase I injector with only the pressure swirl fuel circuit flowing water into atmospheric air.

AIAA-2024-0583 https://anl.app.box.com/v/XrayAeroSpray

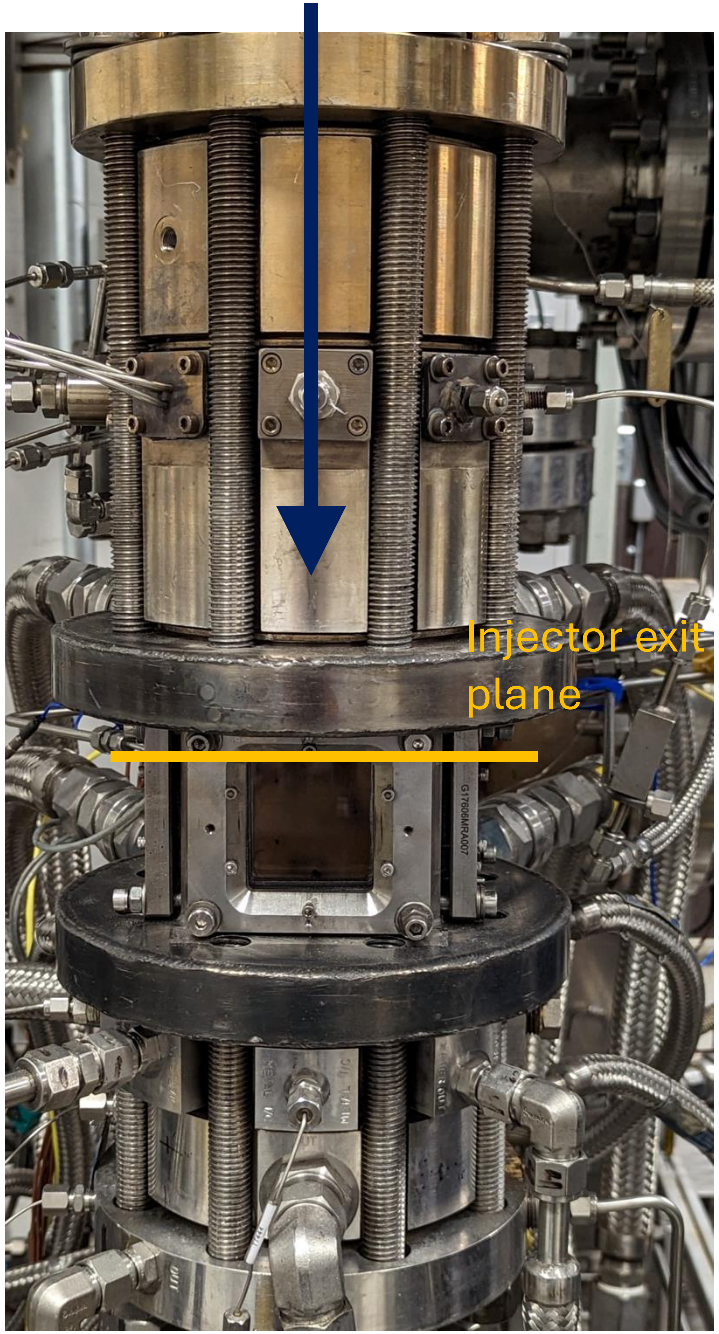
CE-13C test rig at NASA Glenn

- Flow direction, top to bottom
- Three-inch circular cross section
- Three windows for optical access

(2.3-in wide x 2.4-in tall)

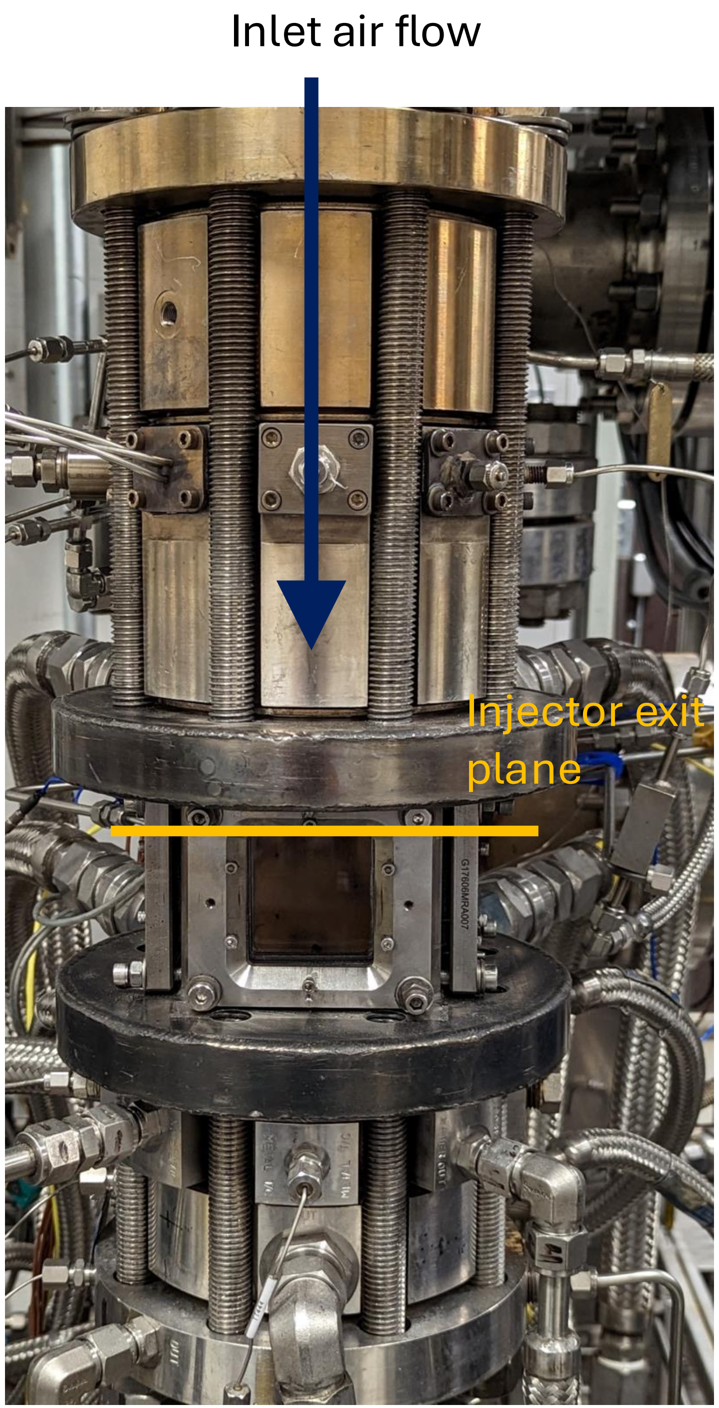
- Exit plane of injector dome near top of window
- Up to 75 psia inlet air pressure
- Up to 1000 F inlet air temperature
- All test points presented with air at atmospheric pressure and room temperature

Inlet air flow



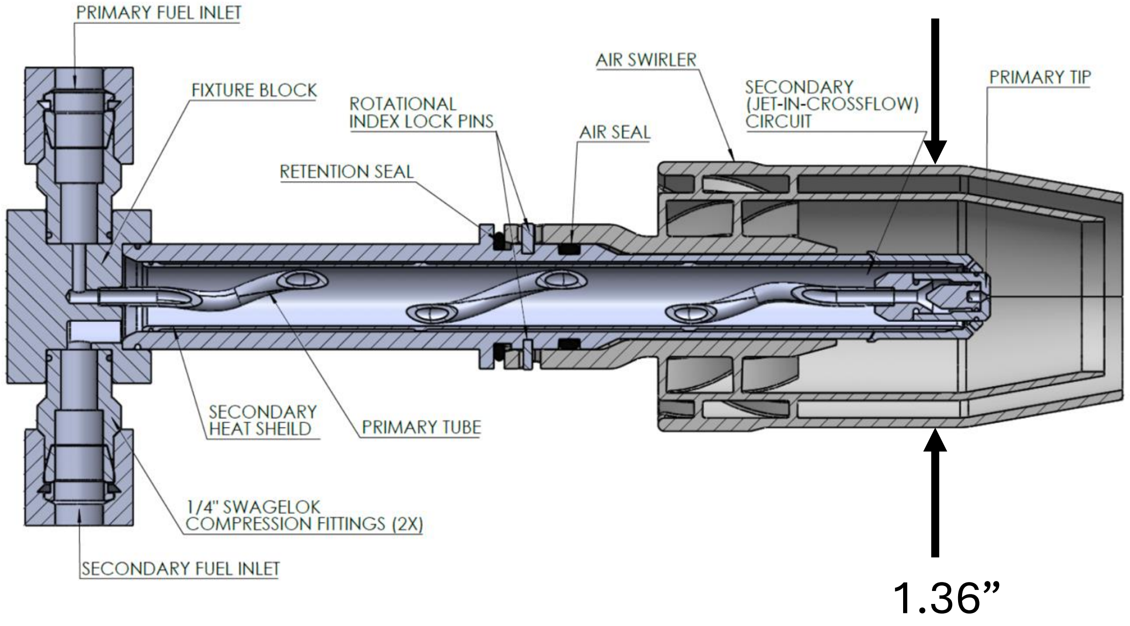
CE-13C test rig at NASA Glenn

- Cold flow testing examined air pressure drops between 1-5%
- Primary spray pressure drops 60-200 psid
- Spray testing with water (instead of jet fuel) allows us to run longer
- Moisture quickly collected on window surfaces degrades image quality
- Removed windows, running semi-unconfined flow



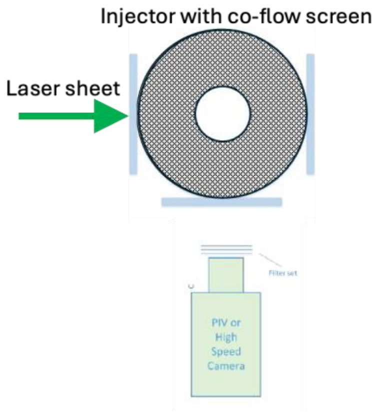
Non-proprietary Phase I “Pri-Sec” Injector

- Two Phase I atomizer configurations were designed and manufactured by Woodward FST in collaboration with government and industry partners
- Pressure swirl atomizer on primary circuit nominally 50-degree hollow cone with flow number 1.5
- Jet-in-Crossflow secondary circuit with four orifices angled 45-degrees relative to axial direction and a flow number of 18.
- Counter-swirling inner and outer axial air swirlers, angled at 45-degrees
- Fuel stem made from metal but air swirler made from acrylic for x-ray transparency at low temperature and pressure in phase one’s work
- Phase two at high pressure, phase three at both high pressure and temperature will require different materials

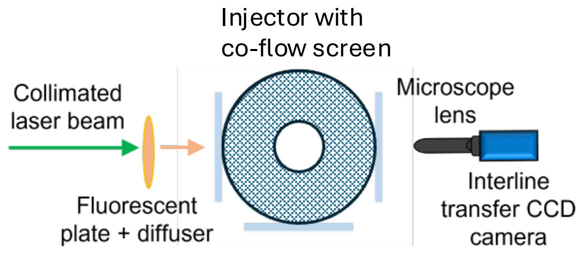


Optical setup, figures showing top-down perspective, flow into page

- Top figure shows particle image velocimetry (PIV) setup, laser sheet enters left-to-right with camera normal to laser sheet
  - Dual head Nd:YAG operating at 15 Hz
  - Image Pro 2M interline transfer CCD camera, 1600 x 1200 pixels
  - Magnification 45 µm/pixel
  - Collected 500 images pairs per data point
- Bottom figure shows shadowgraphy setup where collimated beam strikes fluorescent plate
  - Dual head Nd:YAG operating at 15 Hz
  - Image Pro 2M interline transfer CCD camera, 1600 x 1200 pixels
  - Magnification 1.31 µm/pixel
  - FOV approximately 2.1-mm wide by 1.57-mm high
  - Collected 500 image pairs per data point
  - Three-axis traverse allowed probing in different areas of spray
- Typically begin recording, turn hand valve open, complete 500 image pairs, turn hand valve closed



Setup used for laser sheet imaging (PIV)



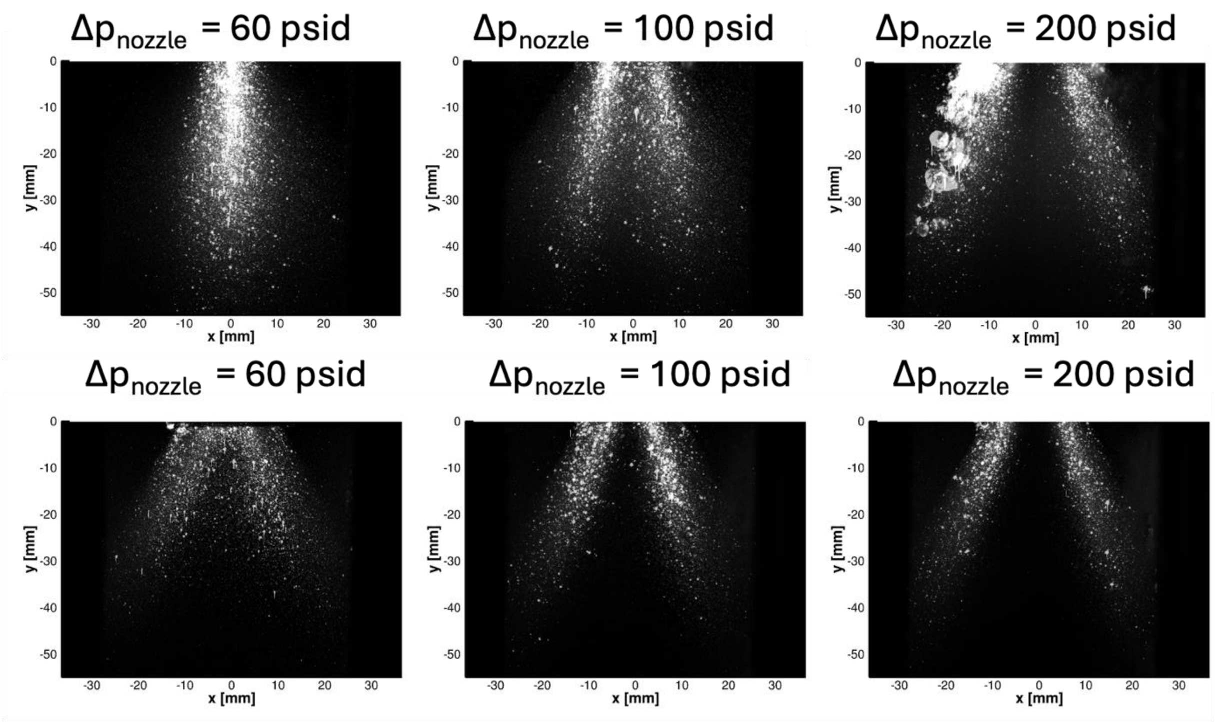
Setup used for shadowgraphy

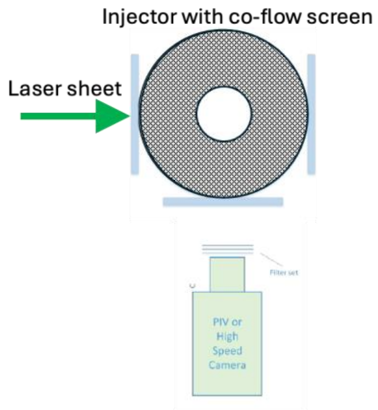
Qualitatively assessing global spray quality from the primary circuit at various “fuel” pressure drops (columns)

- Images of standard deviations over 500 images
- Top row shows spray into quiescent air (no air flow)
- Bottom row shows spray at 3% air pressure drop
- Lower liquid pressure drops indicate poor atomization observed by very narrow spray cone
- Increasing liquid pressure drop showed spray cone developing and appears as hollow cone at 200 psid
- Flowing air also improved spray, allowing hollow cone to develop and open up
- Hollow cone spray evident at 100 psid and higher with airflow, but only at 200 psid without airflow

quiescent air (no air flow)

3% air pressure drop

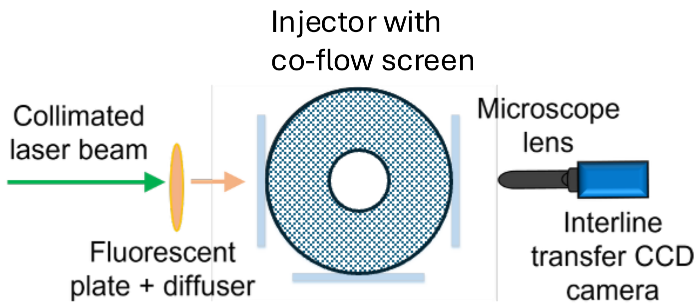




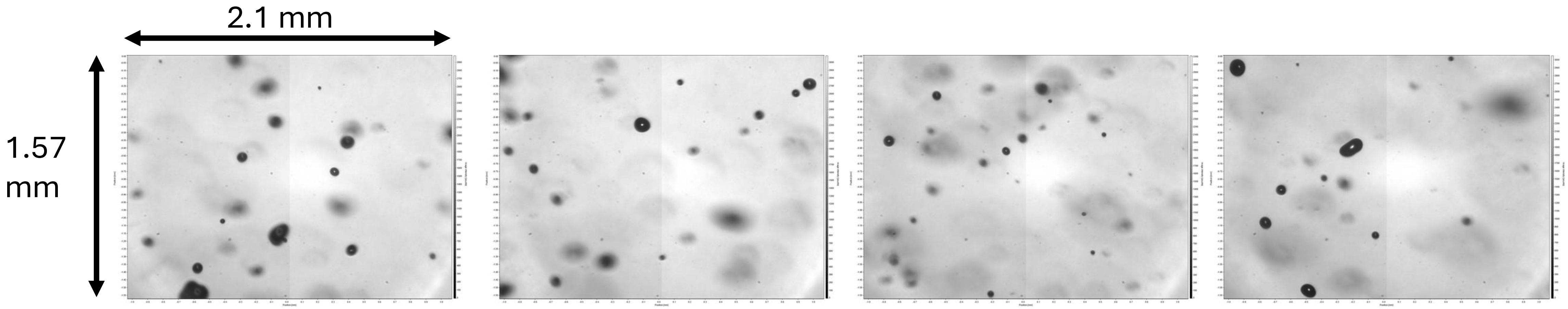
Setup used for laser sheet imaging (PIV)

Sample shadowgraphs of cold flow water spray, 1 mm from injector exit

- Non-consecutive but from same image set at fuel line pressure drop 60 psid and air pressure drop at 3%
- FOV approximately 1.57 mm high by 2.1 mm wide
- Processing to identify droplets, by sharp contrast in liquid-gas interface, that pass through depth-of-field at center plane
- Collected over 500 image pairs and processed statistics, including Sauter mean diameter (SMD)



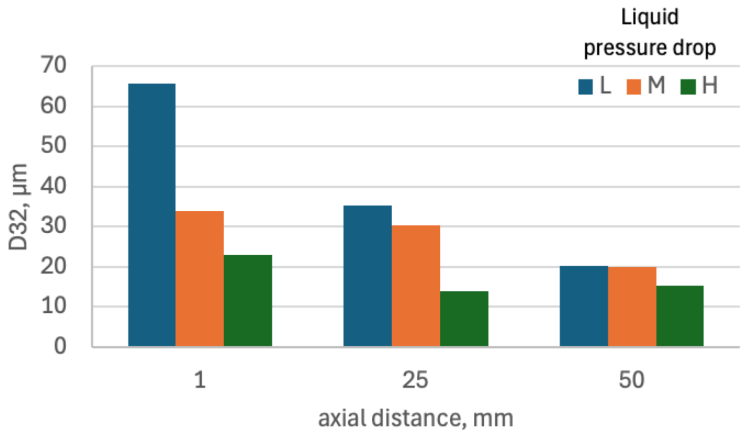
Setup used for shadowgraphy



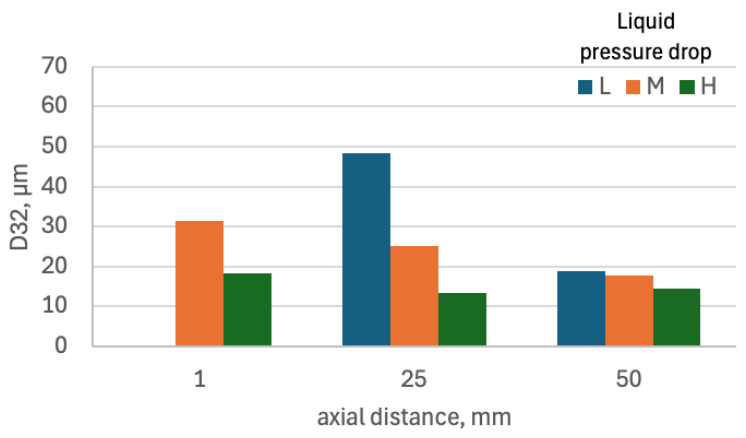
Droplet sizing (SMD) results from the primary circuit at various "fuel" pressure drops

- Columns left to right show air pressure drops at 3%, 4%, and 5% respectively
- Each of three plots show three axial locations at 1 mm, 25 mm, and 50 mm downstream of injector exit, along centerline
- Low, medium, and high liquid pressure drops (similar but not exactly to previous slide) indicated by color
- Largest droplets appeared closest to the dome and decreased with downstream distance as liquid breakup occurred
- Increased liquid pressure drop also decreased SMD, although less effectively at 50 mm
- Increased air pressure drop alone (between 3-5%) typically showed some decrease in droplet sizing at these locations

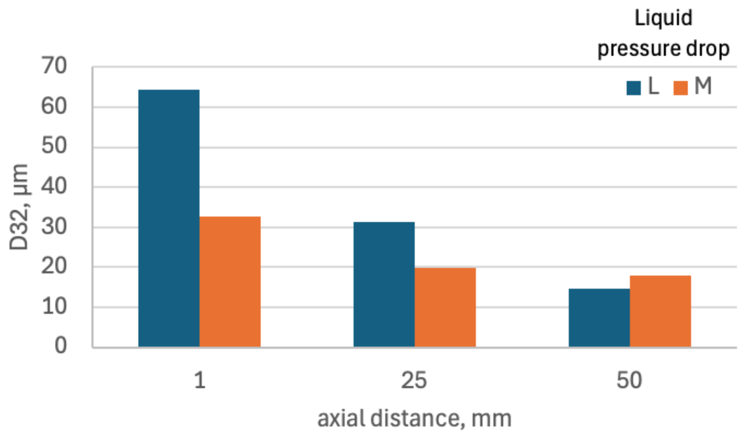
air pressure drop 3%



air pressure drop 4%



air pressure drop 5%



Summary

- Presented droplet sizing and spray visualization to assess performance of a Phase I Aero-Spray non-proprietary injector's primary circuit at atmospheric conditions (running semi-unconfined flow)
- Spray quality from laser sheet imaging showed poor atomization at low water pressure drops near 60 psid, improving with increased $\triangle$P with best quality at 200 psid
- Flowing air helped to open spray cone for better atomization quality when compared to no air flow
- Sauter mean diameter decreased with increased water pressure drop, air pressure drop, and with axial distance away from injector
- The low temperature-pressure Aero-Spray non-proprietary injectors permit testing with current ANL Advanced Photon Source capabilities and permit using materials with high x-ray transmission properties.
- Future testing with non-proprietary injectors designed for higher temperatures and pressures will enable obtaining atomization data at realistic combustor conditions

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