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Rocket-Engine Injector Development— A Case Study of a Single Injector



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S. Alexander Schumaker
Stephen A. Danczyk

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Industry Drivers

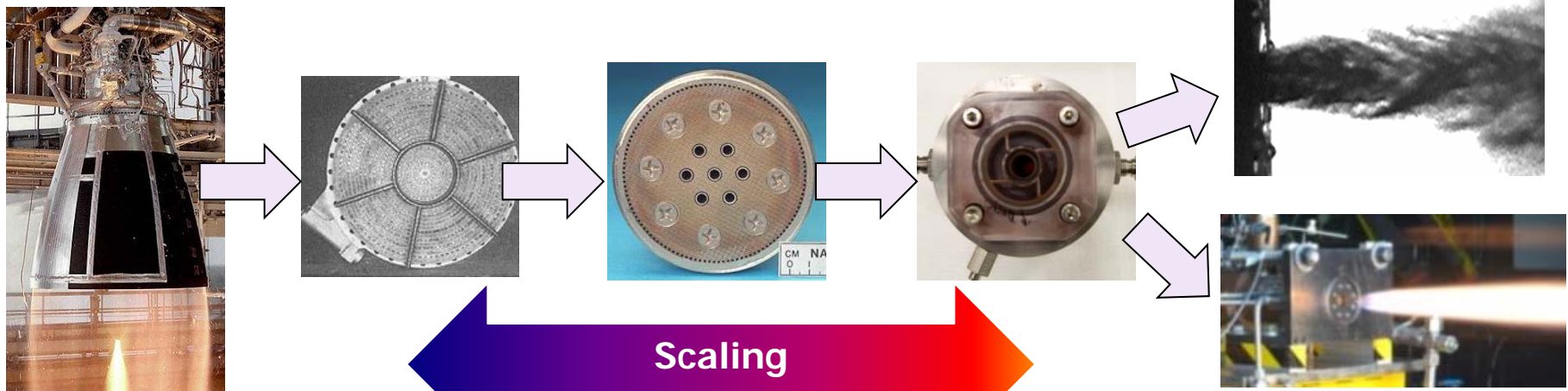


- **There is arguably more liquid rocket engine development going on in the US today than at any other time in the last 30+ years**
 - More “commercial” companies are entering the market
 - NASA’s mandates to move beyond earth orbit and retirement of the shuttle
 - AF on-going needs (move away from Russian-built engines, replace aging satellites, etc.)
- **Cost has become a main driver in these markets, but increasing performance parameters is still important to enable new missions**
- **Past rocket development been largely empirical using full-scale tests and a build-bust-redesign approach**
- **This approach is very costly and encourages incremental progress which can be inhibiting to revolutionary discoveries**



Cost Reduction

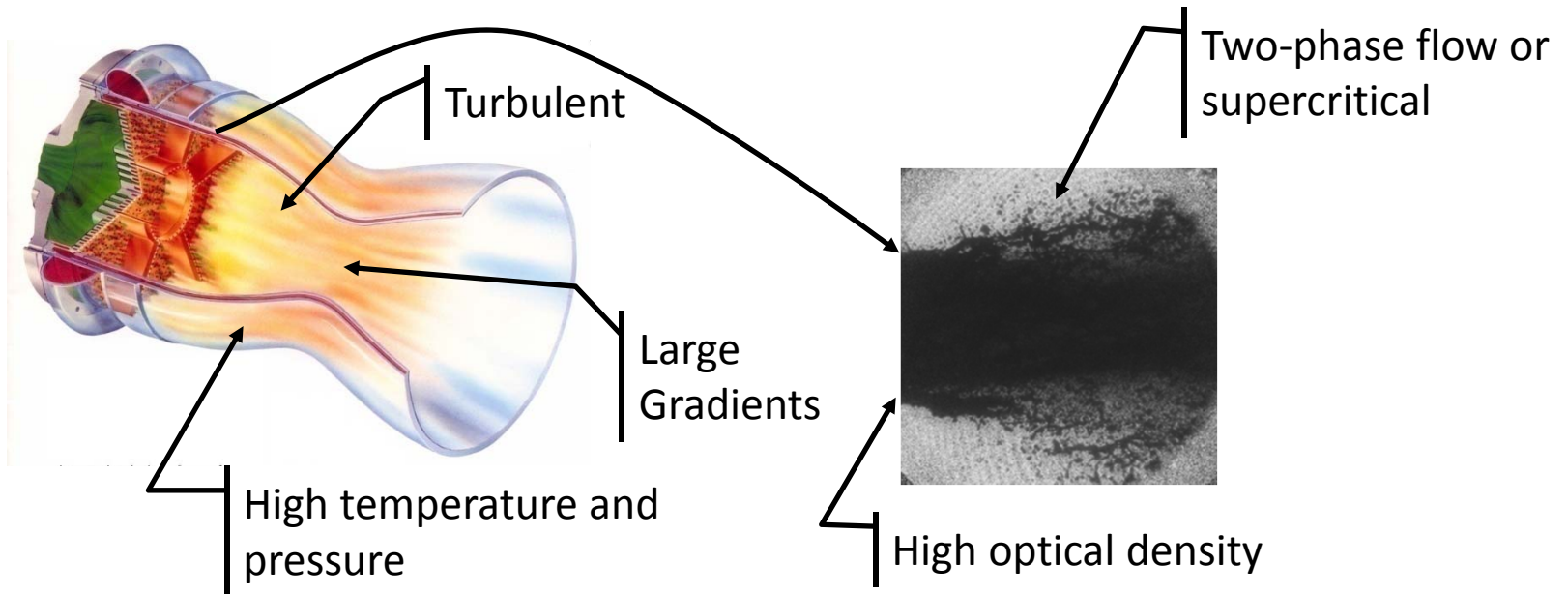
- To reduce costs we need to rely more on modeling and on low-cost (“subscale”) testing before full-scale tests
- Models and low-cost testing approaches need to be demonstrated to be predictive prior to use
- AFRL has several programs to study individual subcomponents of the engine
 - This talk focuses on the injector component



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Boost-Class Rocket Engine Injectors



- **Items of importance in terms of the injector component**

- Atomization and mixing of the propellants—determines engine performance (efficiency)
- Sets the environment for the wall (heat transfer)
- Key for enabling pressure balance and combustion stability

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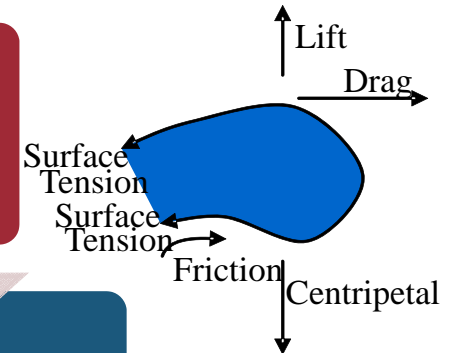


Developing Design Methods



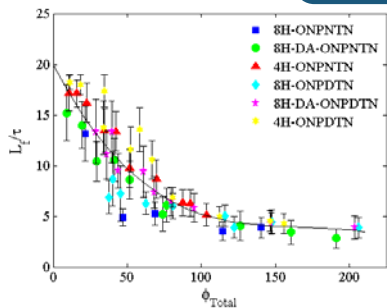
Generalized Analytical Model

- Model for gas-phase-dominated atomization is a balance of forces on a disturbance



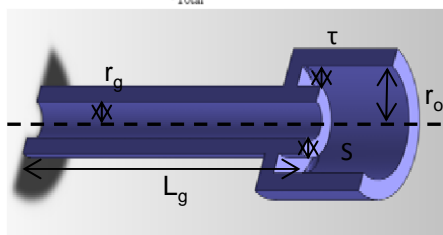
Scaling Laws

- Momentum flux ratio collapses data
- Aerodynamic forces dominate, surface tension not important



Design Criteria

- Process established for single injector type
- Encompasses geometric design details and recommended testing for verification and refinement



Injector Design and Hot-Fire

- Design injector and verify performance predictions and scaling in a combusting environment



Empirical Models



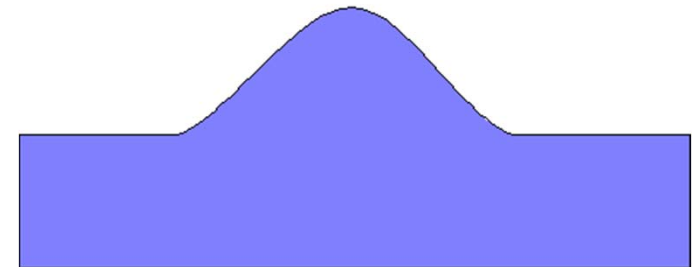
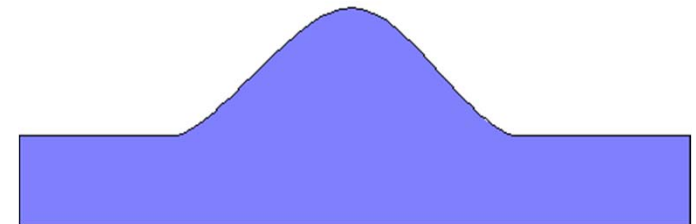
- **Empirical models exist for numerous types of injectors and have been developed for some rocket injectors over the years**
- **US experience is largely with hydrogen-oxygen engines, so correlations for injectors are typically developed for the conditions that apply there**
- **Move in the AF to liquid hydrocarbon engines, with very different mixture ratios and flow rates than hydrogen-oxygen engines**
 - Applying correlations outside of their applicability can lead to very large errors
- **Additionally, reliance on empirical correlations defines a design and operating box prematurely—preselects against revolutionary design**



A Simplified Viewpoint



- To build a generalized atomization model, start by simplifying the problem down to the creation of a single droplet
- There are several ways that this may occur depending on the forces involved
 - These are examples for situations where the gas-phase strongly participates in the droplet-making process
- Two important processes—**disturbance creation and growth / deformation to create droplet**



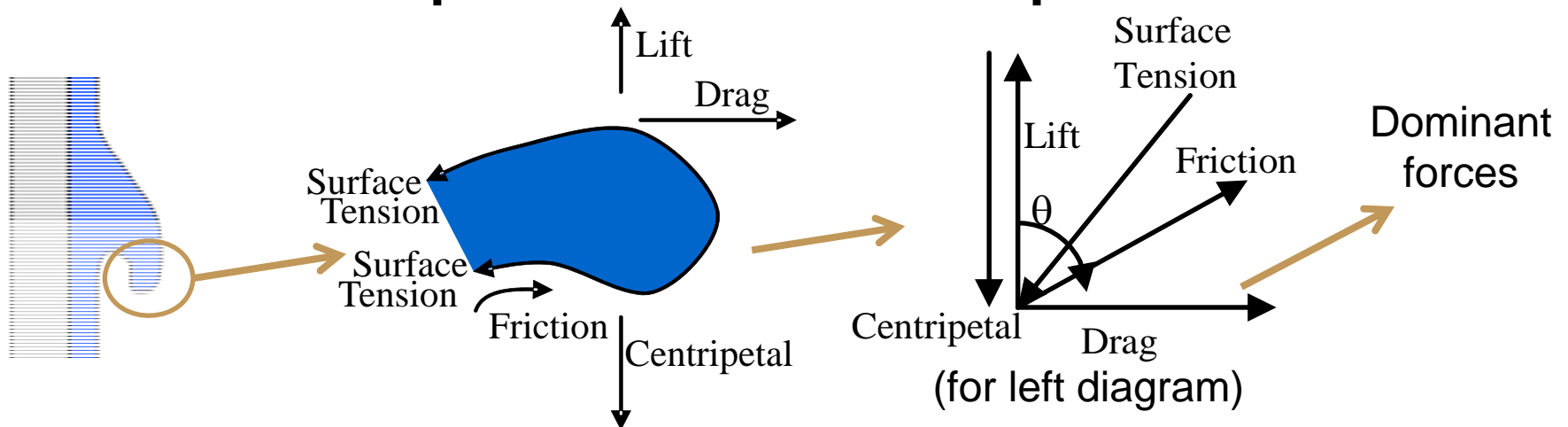
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Generalized Atomization Model



- Based on a balance of forces acting on a disturbance of the liquid-gas interface
- Forces cause distortion of the disturbance until a portion of the disturbance finally separates from the bulk of the liquid and become a droplet



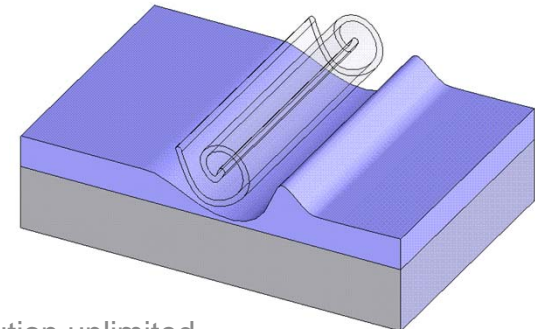
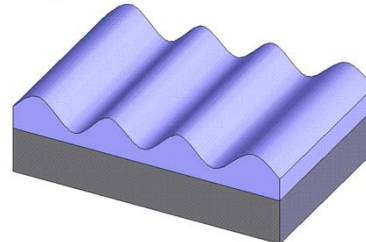
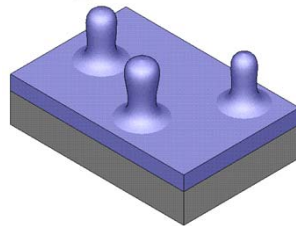
- Could also provide estimates of initial droplet size and number if the initial disturbances were known



What is a Disturbance Type?



- There are various disturbance initiation mechanisms which each generate slightly different disturbances on the film
- Before the theory can be applied, disturbance types must be identified
 - A review of film literature suggested four main disturbance types
 - Ligaments due to liquid turbulence
 - Waves due to hydrodynamic instabilities
 - Wave-like structure(s) caused by large-scale gas-phase structures
 - Ligaments due to gas-phase turbulence

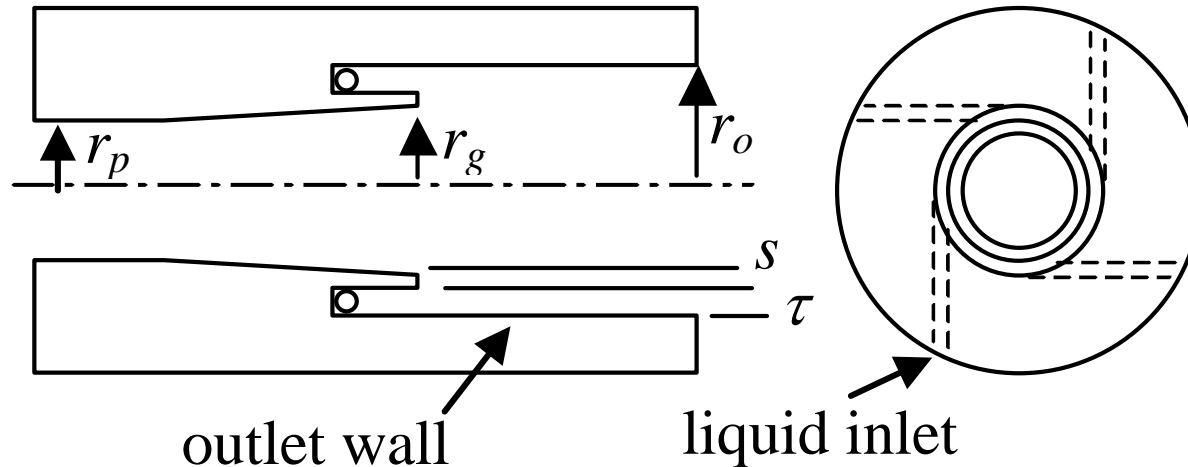




Gas-Centered Swirl Coaxial injector



- Injector is of interest in oxygen-rich cycles using hydrocarbon fuels, and is similar to what is used on Russian-built kerosene engines



- Swirling liquid is introduced along the wall creating an annular sheet
- Sheet is sheared and atomized by a high-velocity annular gas flow (unswirled)

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Scaling



- **The generalized atomization description can provide scaling guidance to be used for lower-cost testing and as design criteria**
 - Specifically, testing at atmospheric conditions is desirable, since pressures needed to match density ratios seen in engines are 40-65 atm

$\frac{\rho_g v_g^2}{\rho_l v_l^2}$	Aerodynamic (shear)	$O(10^2)$ - $O(10)$
$\frac{1}{Re_l}$	Viscous	$O(10^{-2})$ - $O(10^{-3})$
$\frac{1}{We_l}$	Surface tension	$O(10^{-2})$ - $O(10^{-4})$
$\left(\frac{v_{rot}}{v_l}\right)^2$	Centrifugal	$O(10^{-2})$ - $O(10^{-3})$



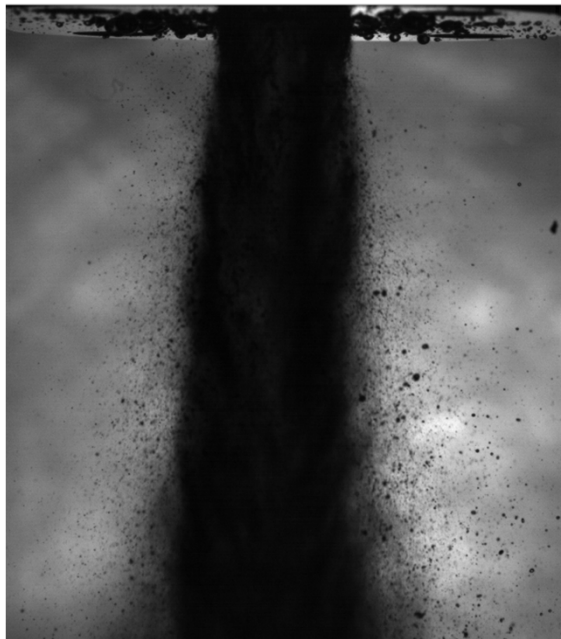
2+ orders of magnitude larger. Responsible for first-order effects



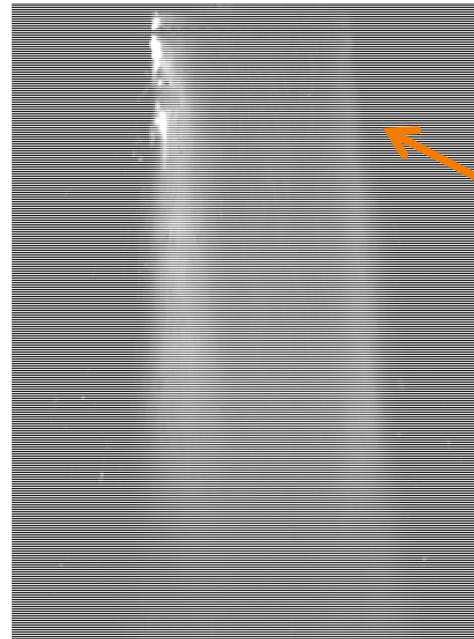
Verification of Scaling



- For predicting combustion performance, droplet size, velocity and number density are important
- The optical density of the spray has prevented making these measurements



Broadband Backlight



Laser Sidelight

Scattering
attenuates
laser signal



Intact Liquid



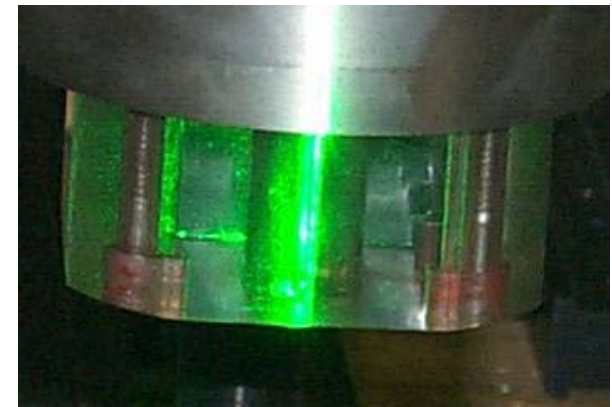
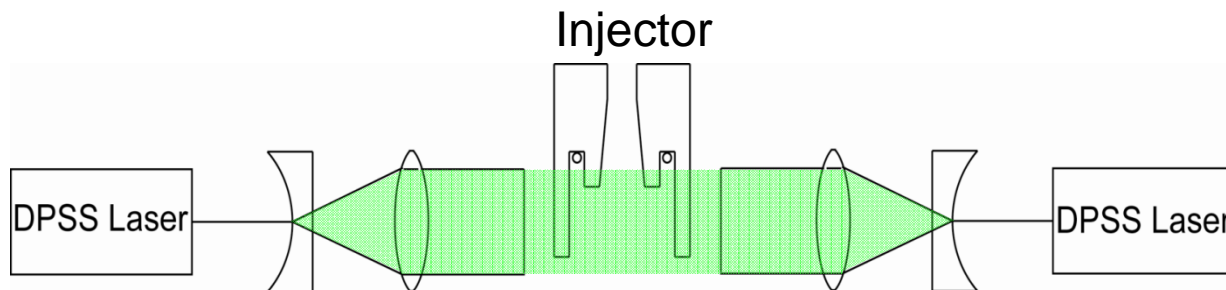
- **The majority of atomization for this injector occurs within the injector body where optical density is lower**
 - Measurements of the intact liquid length and the change in height along the injector's axis can be made
- **Atomization rate is often related to atomization performance, so we will use intact liquid length for verification**
 - This is not a unique approach, it's been used in rocket studies of shear coaxial injectors for decades ("dark core length")
 - But this is an annular liquid sheet, so access is difficult and correspondence with earlier work on shear coaxial jets is unlikely



Experimental Set-Up



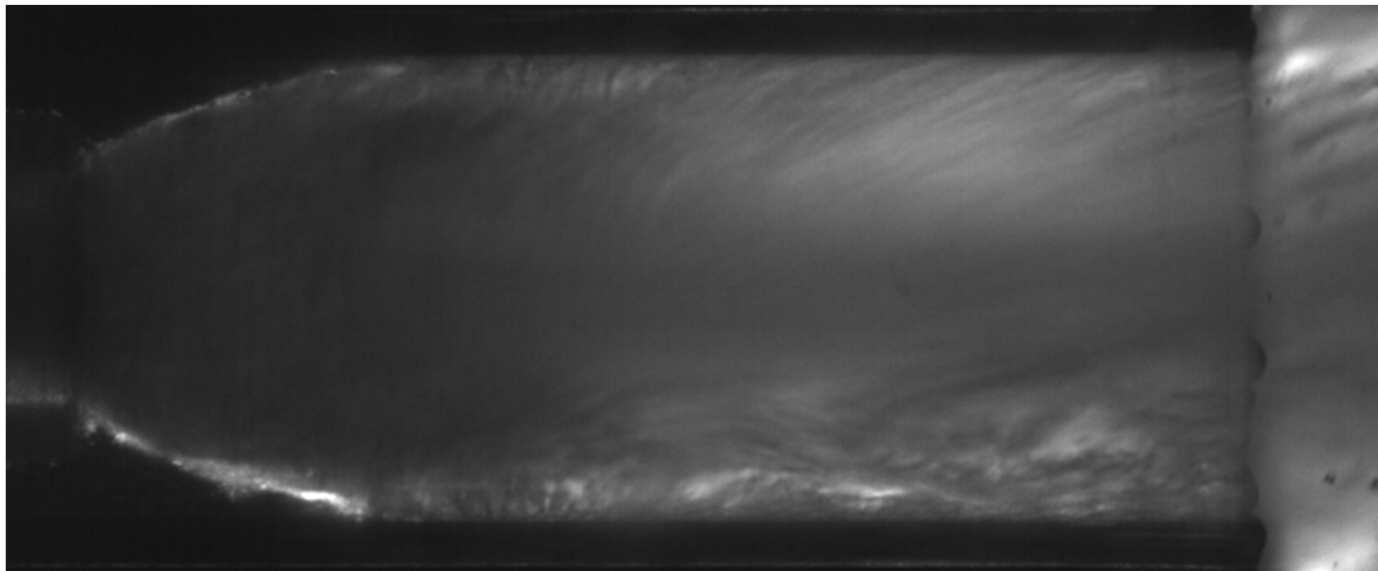
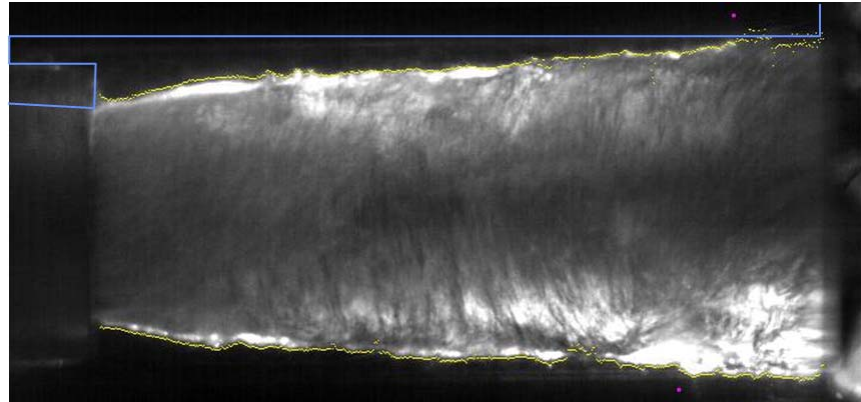
- **Dual-laser sheets just off of injector centerline, perpendicular to the camera**
 - Slight off-center of fractions of millimeters greatly improves forward scattering of light
- **Modular injector constructed to change (independently) swirl level, outlet diameter, initial thickness for liquid and height of shelter**



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Inside the Injector

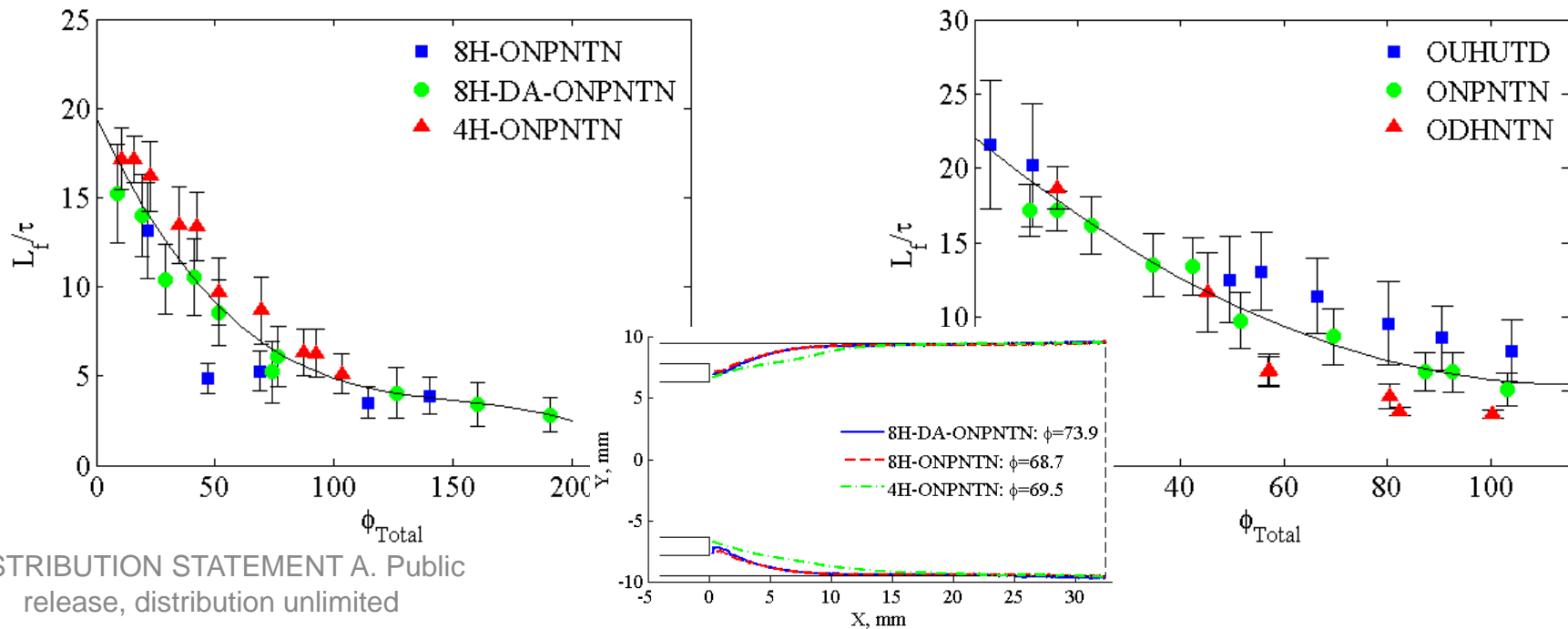


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Does Scaling Work?

- **How do we define a single velocity for the liquid and gas in this dynamic environment?**
 - Because we want to use this approach for low-cost experiments, definitions must be a priori
 - Basic velocity definitions based on set mass flow rates and inlet diameters were used



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Swirl Effects



- **Agreement is good, and there is something very surprising, the vector of the liquid velocity is not important for scaling atomization rate**
 - If annular velocity of liquid is used then data collapses into families of curves based on swirl level—indicates that experiments vary swirl enough to capture any effect
 - Simplified velocity definition does not capture the acceleration of the liquid and gas which may play a role here
 - Swirl merits additional investigation



High Swirl



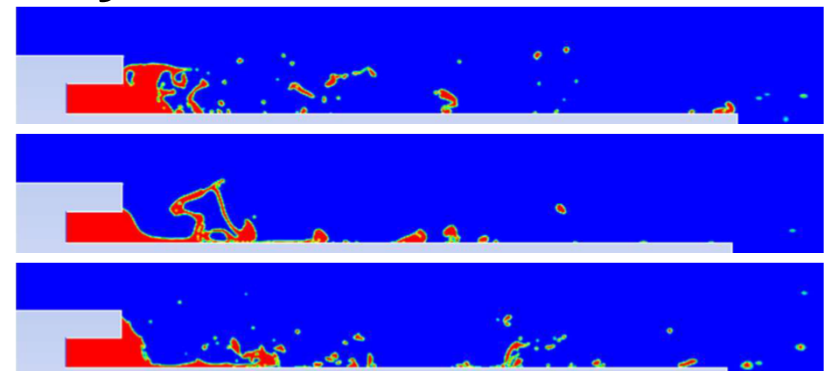
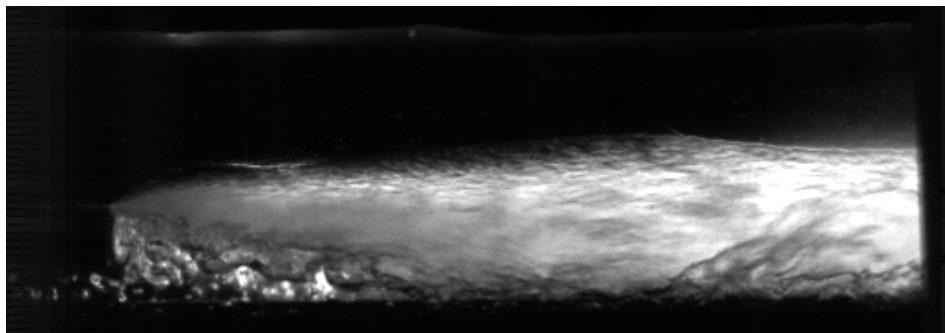
Low Swirl



What about Zero Swirl?



- To further investigate, we considered the extreme case where there is no swirl
- As expected, lack of swirl creates a very dynamic film which, on average, atomizes more rapidly than the swirling film
- However, a good boundary condition (filling of the sheltered area) cannot be achieved and dynamics are severe enough to disrupt velocity and rms measurements in a flat geometry

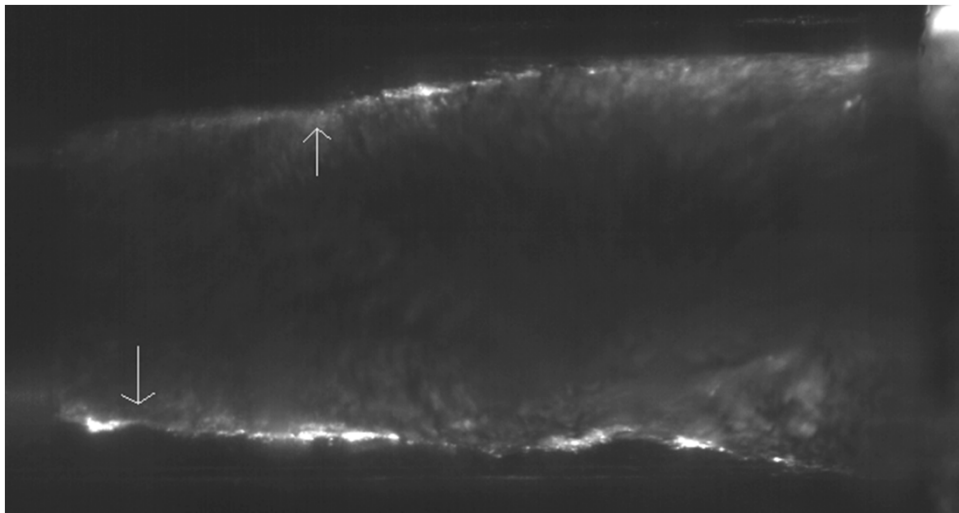




More Complexities

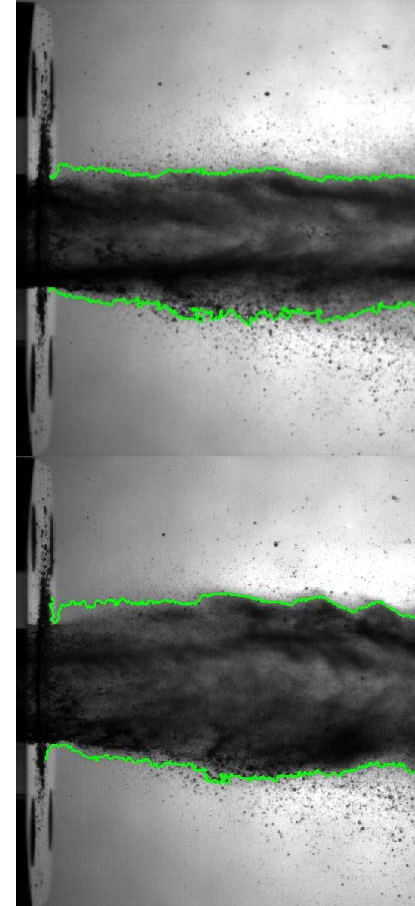


- **Additionally, some of the film boundaries clearly exhibited periodic instabilities**
 - Frequencies in atomization can couple with combustion and the rocket chamber and be catastrophic



“Pulsing” behavior

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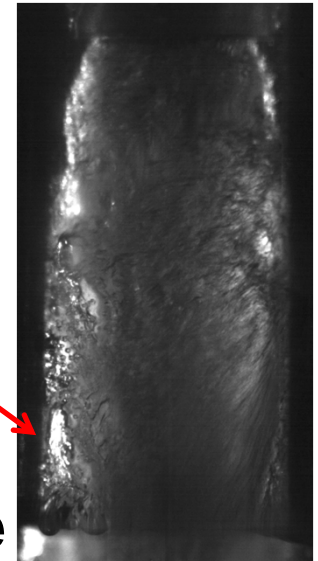
Comparison of Unsteadiness



- **Flapping appears to be caused due to complex flow separation at the injector exit**

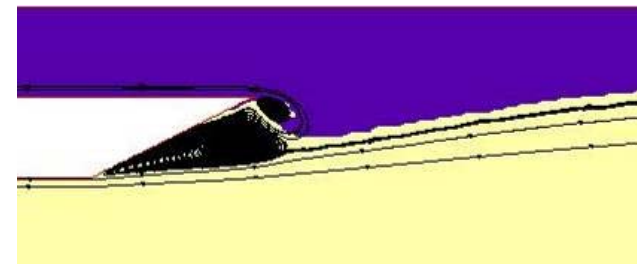
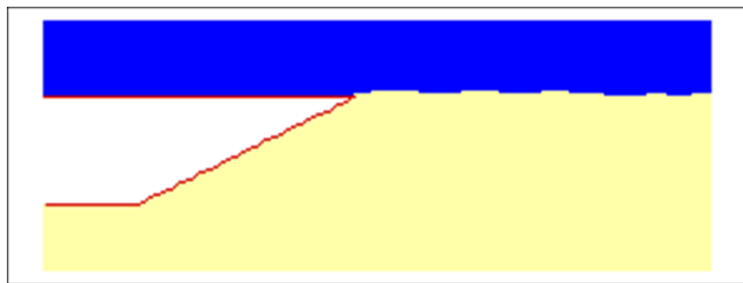
- This is a fundamentally 3D, unsteady process that is complex and costly to model, so it has not yet been attempted

Entrained,
no droplet
flow



- **Pulsing is (nearly) axisymmetric, can a simple computational model help us understand this behavior?**

- Axisymmetric with swirl using FLUENT and its VOF model for the boundary



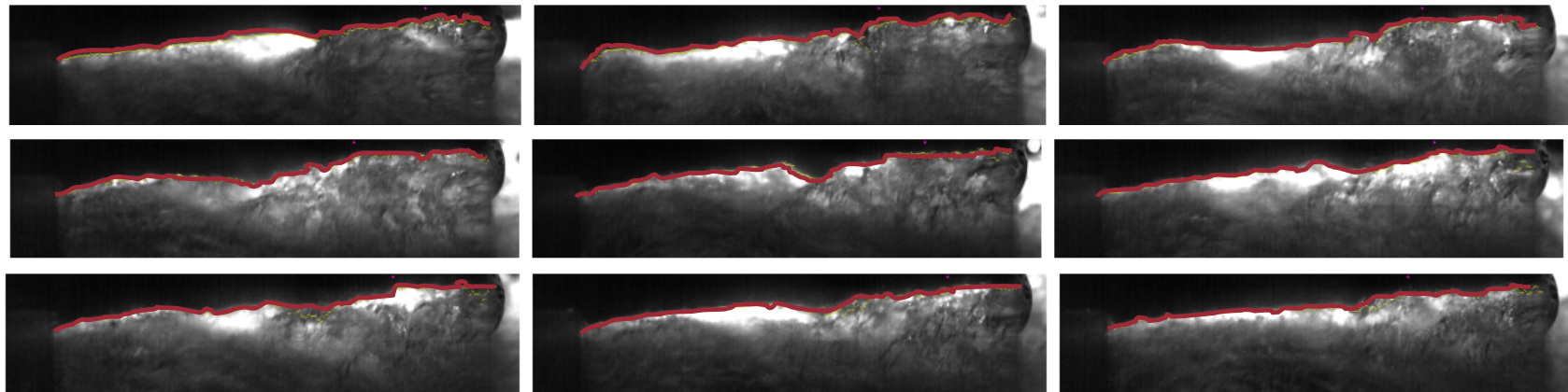


Comparison of Unsteadiness



Axisymmetric CFD (VOF in Fluent) results every 1.5 ms

Experimental results every 0.5 ms, MFR $\sim 10^*$ above results



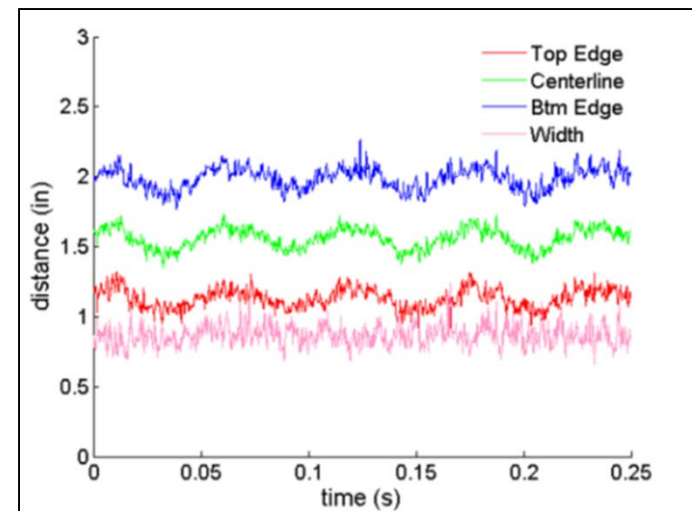
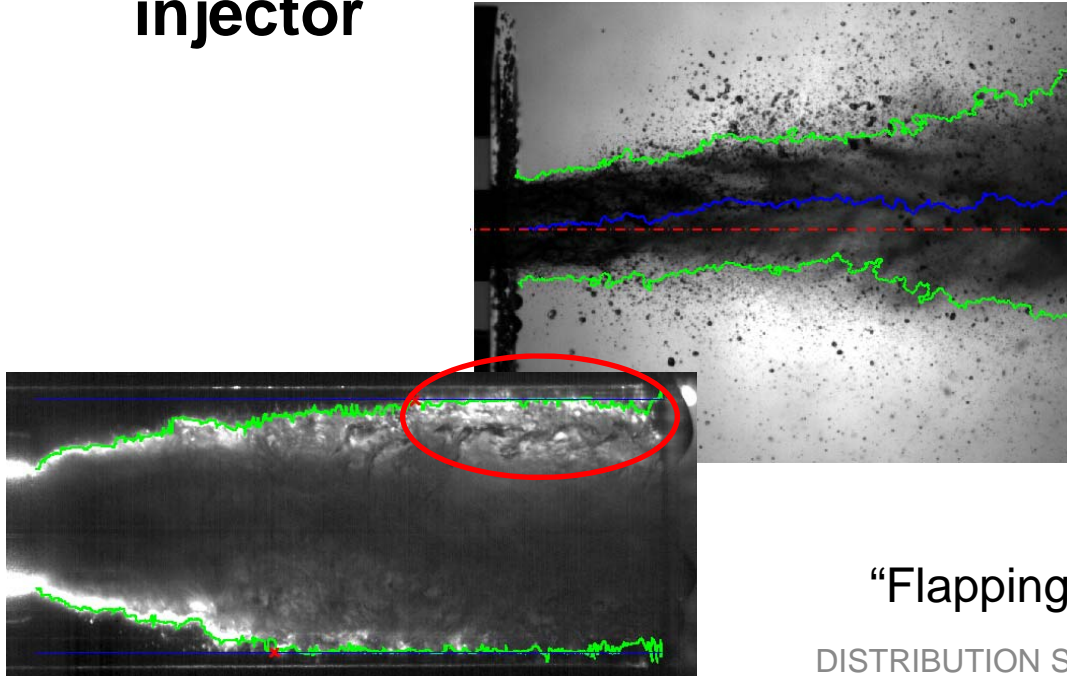
- **While qualitative agreement can be achieved between model and experiment, not at matching conditions**



More Complexities



- **Complex interactions involving swirl and the sudden expansion created other periodic behaviors**
 - This flapping could impact mixing between injectors or the heat transfer to the wall of the combustion chamber
- **Both periodic behaviors can be controlled through injector geometry—at the lip or at the outlet of the injector**



“Flapping” behavior

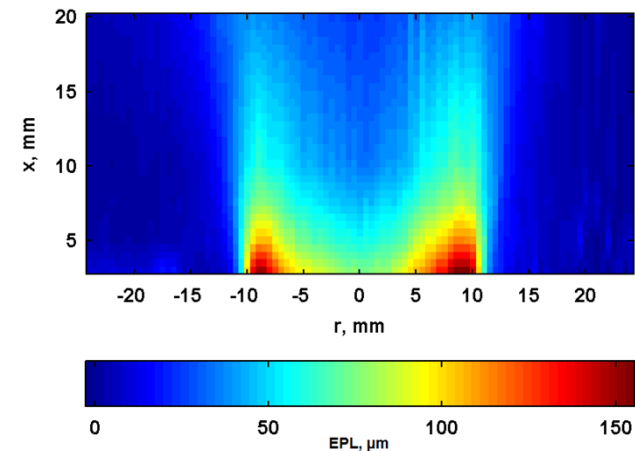
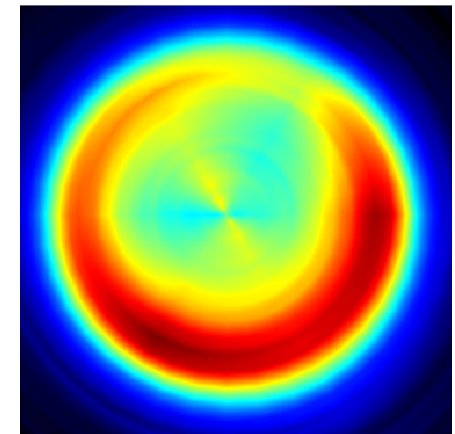
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Other Diagnostics



- **Other, cutting-edge techniques have been developed by AFRL or through AFRL funding in an attempt to overcome the challenges of optically dense sprays**
- **Time-gated ballistic imaging provides a shadowgraph of large (intact) liquid structures at the injector outlet**
 - Gate only admits singly-scattered photons
- **X-ray radiography provides mass distribution and mass-weighted acceleration information**
 - X-ray interaction with water is predominantly absorbing, not scattering
 - High-power source at Argonne National Laboratory makes quantitative measurements easily achievable



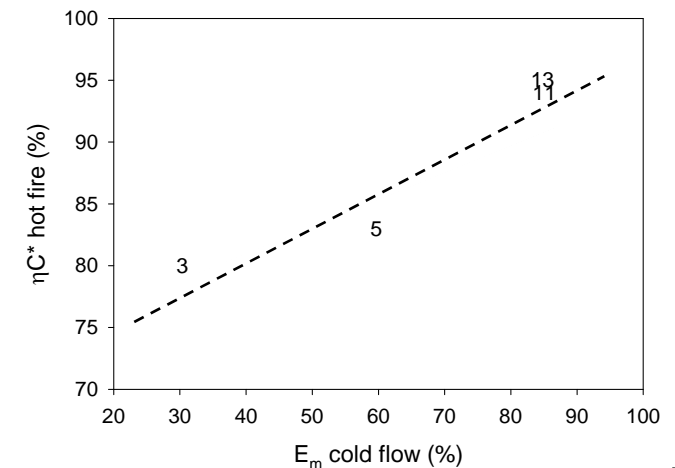
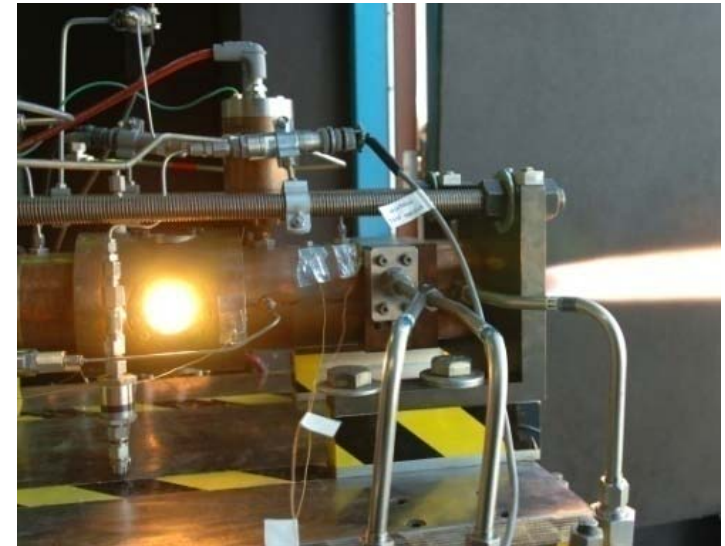
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Combusting Flows



- **Combining data provides a set of design criteria**
 - Includes recommendations for testing needed to verify the design and for design refinement
- **Demonstrating that these cold-flow-derived guidelines are effective predictors of hot-fire performance is needed**
- **C* efficiency measurements from very similar injectors indicate basic approach is sound**

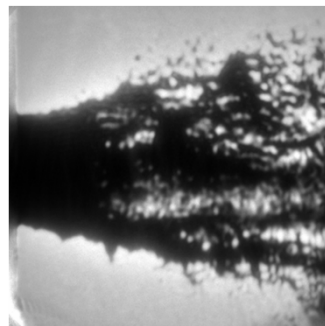




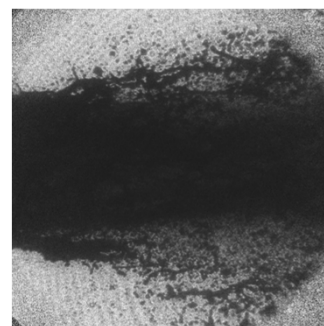
Hot-fire Results



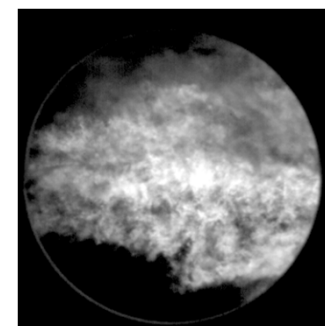
- **Window has thus-far provided only qualitative video images**
 - Optical density due to soot and line-broadening effects have prevented us from collecting temperature and/or species profiles from CARS, PLIF, chemiluminescence and similar techniques
 - We've helped developed high-speed laser techniques to overcome some of these issues
- **Highly instrumented engine will provided additional high-quality quantitative data in the future**



Cold-flow
Ballistic Imaging



Cold-flow
Shadowgraphy



High-speed
Flame Image



Future Outlook



- **The process of developing design criteria for an injector has been briefly reviewed from initial identification of basic physical models through scaling laws to greater complexity**
- **The developed guidance is useful for reducing engine development costs because a feasible design can be achieved more quickly and lower cost testing can be used for refinement**
- **Details of our recommended approach are already being utilized BUT there is much work that remains**
 - Demonstrate applicability in combustion environment
 - Integrate into CFD and show its predictive capability
 - Move beyond single injectors—injector interactions with other injectors and walls