Perspectives on “Reference Sprays” for aligning the spray community

ILASS-Americas Webinar

Aerospace Propulsion and Power Technical Committee

Virtual

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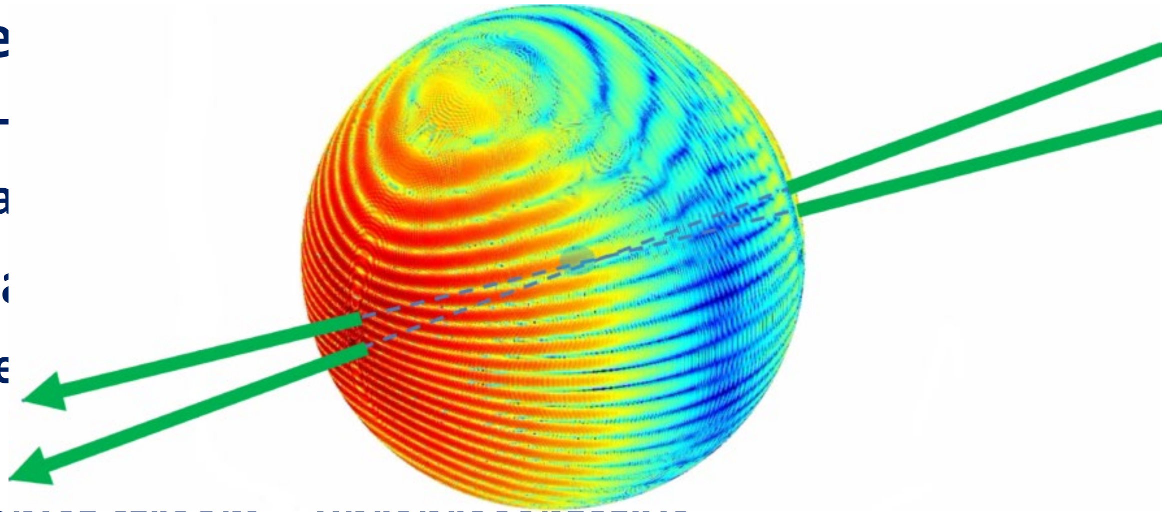
Vincent McDonell

UCI Combustion Laboratory

UCIrvine | University of California

Motivation

- **The Vast Majority of Diagnostics for Sprays take Implicit Measurements**
  - They measure one quantity and then infer the desired quantity
  - Especially the case for laser diagnostics
  - Laser diffraction, PDI, LIF, holography
  - Non-spherical droplets pose an issue
- **Diagnostics Require**
  - Account for errors –
  - Account for accepta
- **Most Diagnostics Ha**
  - Heuristic approache
  - Based on empirical
  - Monodispersed droplet stream – unrepresentative
  - Laser diffraction use a reticle* of a known size distribution – static

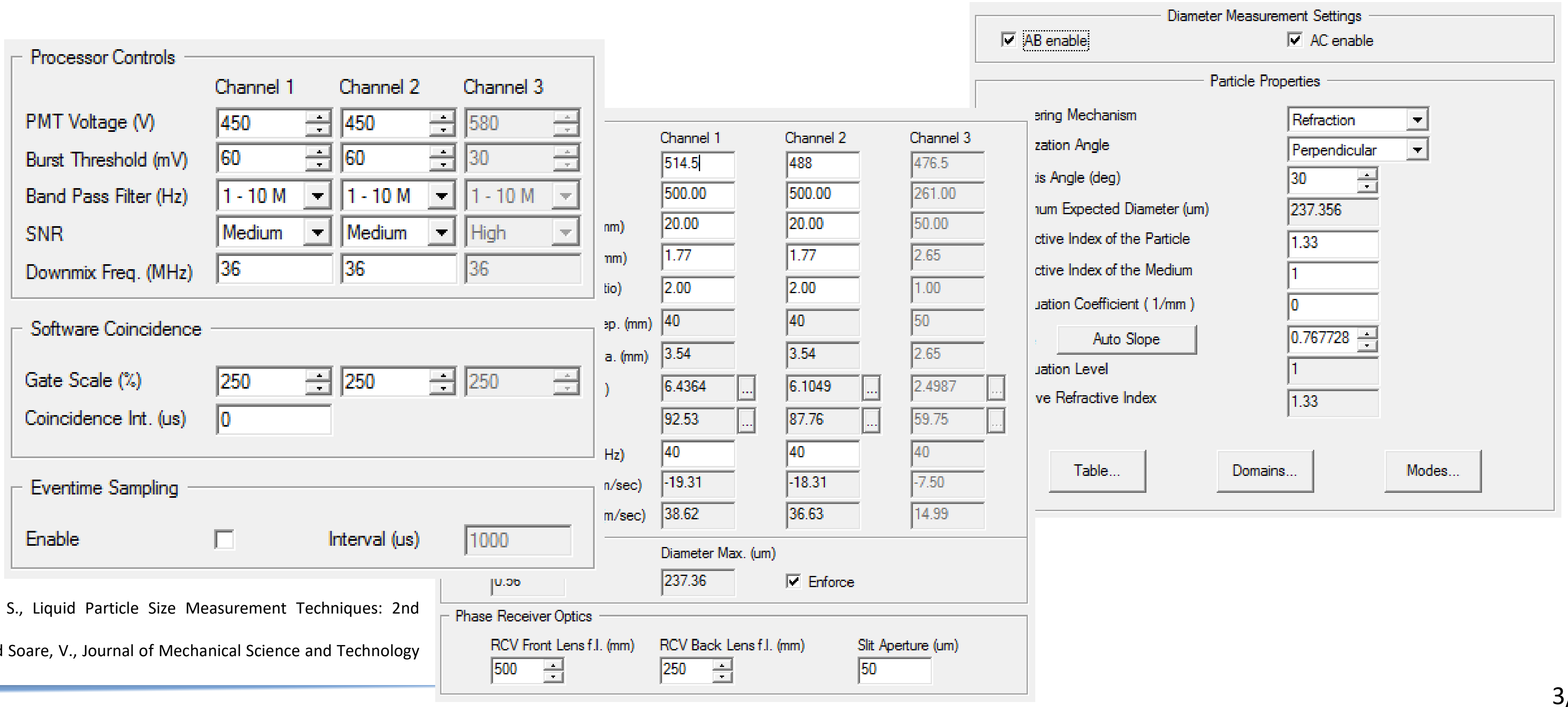


Courtesy of Artium

* e.g., Mühlenweg, H. and Hirleman, E.D., Part & Part Sys Char, vol. 16, no. 2, pp. 47–53, 1999.

Motivation

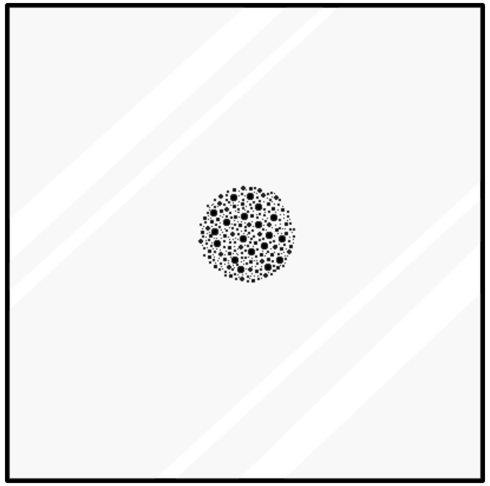
- **Operator Dependent**
  - **It is easy to tweak diagnostics to give data which seems correct – but may be erroneous**
  - **Calibration techniques (e.g. laser diffraction reticle) can similarly be duped**
  - **Validation of settings are time consuming and difficult**



McDonell, V. G., Samuelsen, G. S., Liquid Particle Size Measurement Techniques: 2nd Volume: 170-189 (1990).
Payri, R., Araneo, L., Shakal, J. and Soare, V., Journal of Mechanical Science and Technology 22-8: 1620- 1632 (2008).

Motivation

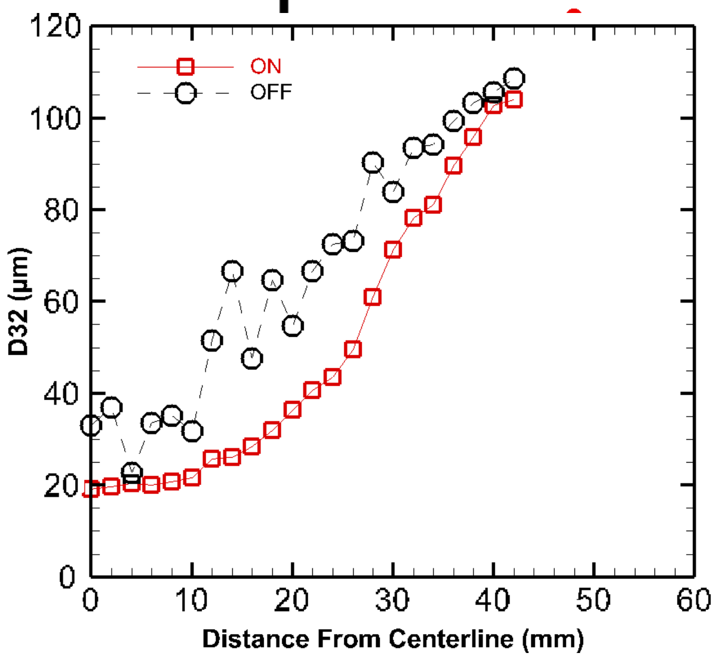
- **Laser Diffraction – Calibrated using a Reticle**
  - **Within 2% of the reticle distribution considered sufficient**
  - **Care was taken with alignment**
  - **Only parameters required are optical**
  - **“Turn key”**
- **PDI – PDPA/PDA Systems**
  - **Advice from manufacturer, “best practice”**
  - **Detector Gain (PMT) voltage**
  - **Burst threshold**
  - **Signal-to-Noise ratio**
  - **Software coincidence**
  - **Intensity validation**
  - **“Requires Expertise”**
- **All subjective / problem dependent**

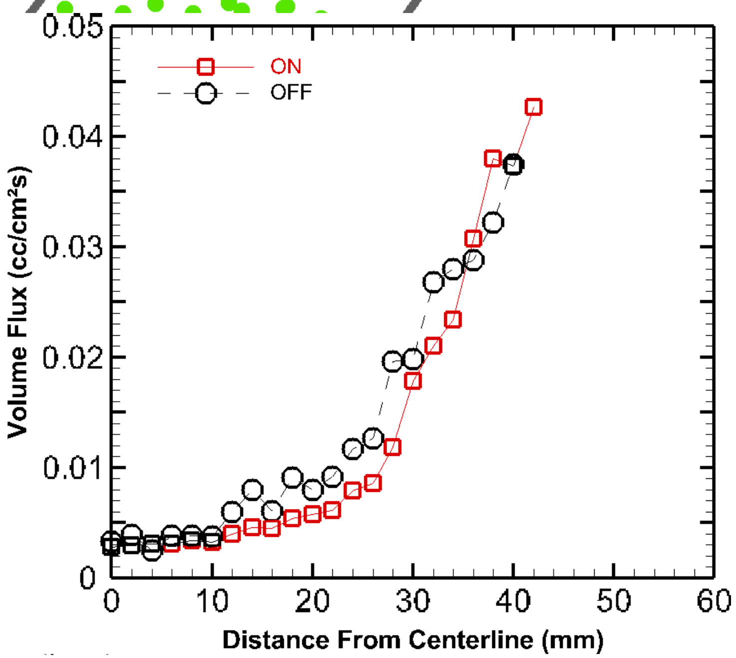


Mühlenweg, H. and Hirleman, E.D., Part & Part Sys Char, vol. 16, no. 2, pp. 47–53, 1999.

Motivation

- **Example: PDI--Effect of Intensity Validation**
  - **Intensity Validation: Sets Reasonable Signal Intensity Range for a given Droplet Size**
  - **Ignores Measured Droplets Outside of these Bounds**





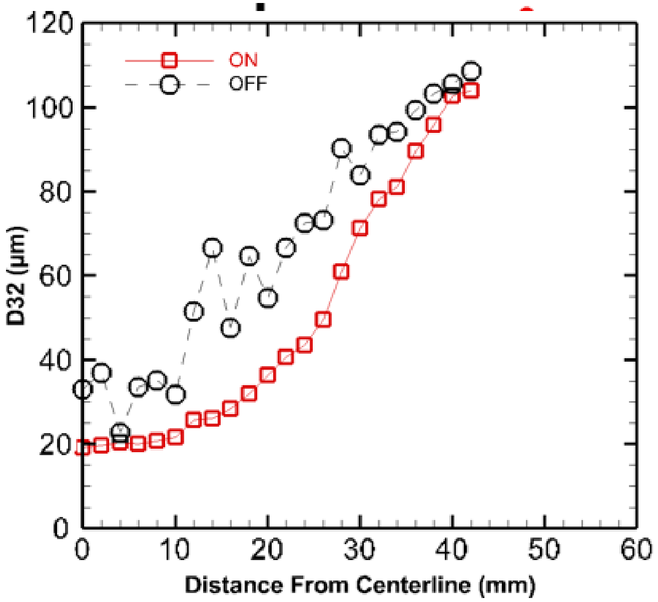
- **While emphasis here is on experiments….same situation exists for simulations involving modeling approaches**

Motivation

- Nominally Similar Test Conditions/CFD models May Produce Different Results
  - Differences due to diagnostic/code/model
  - Differences due to operator
  - Differences due to laboratory conditions
  - Differences due to boundary conditions

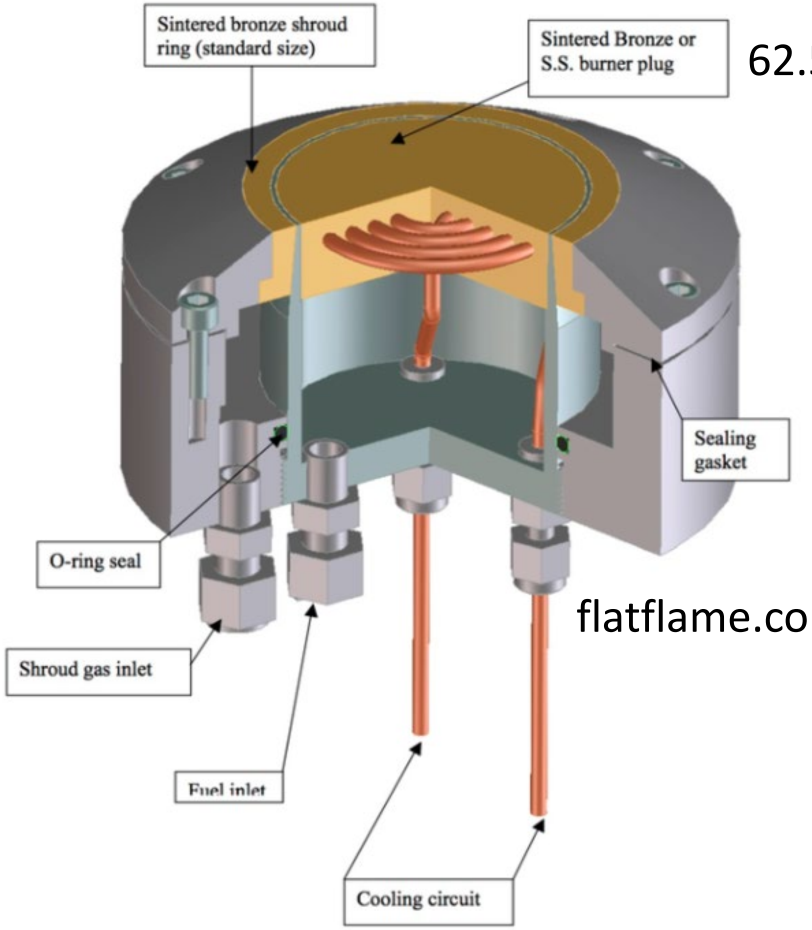
- Is it possible to compare results between workers from different labs, using some different test conditions, different instruments, and different operators?
  - Experiments and Simulations
    - ✓ "Experimentalists are from Mars, Modelers are from Venus"
      - – Considerable rhetoric over need to work together

- A "reference spray" can potentially address
  - Appropriate confidence intervals on spray characteristics under pr
    - ✓ Pressure, temperature, spatial location
    - ✓ Steady, robust, reproducible spray
    - ✓ SMD, D10, D50, D90



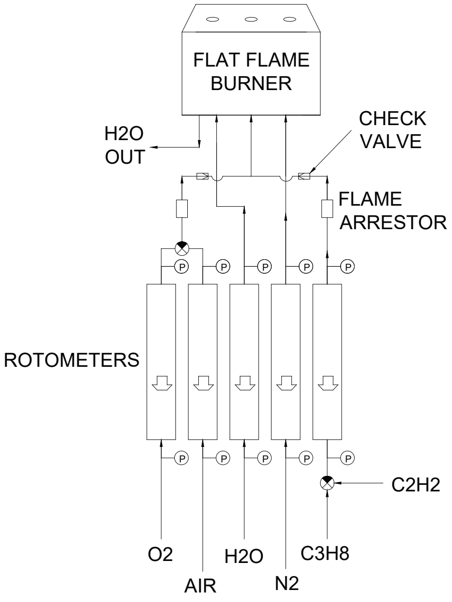
Analogous Combustion Reference Flame

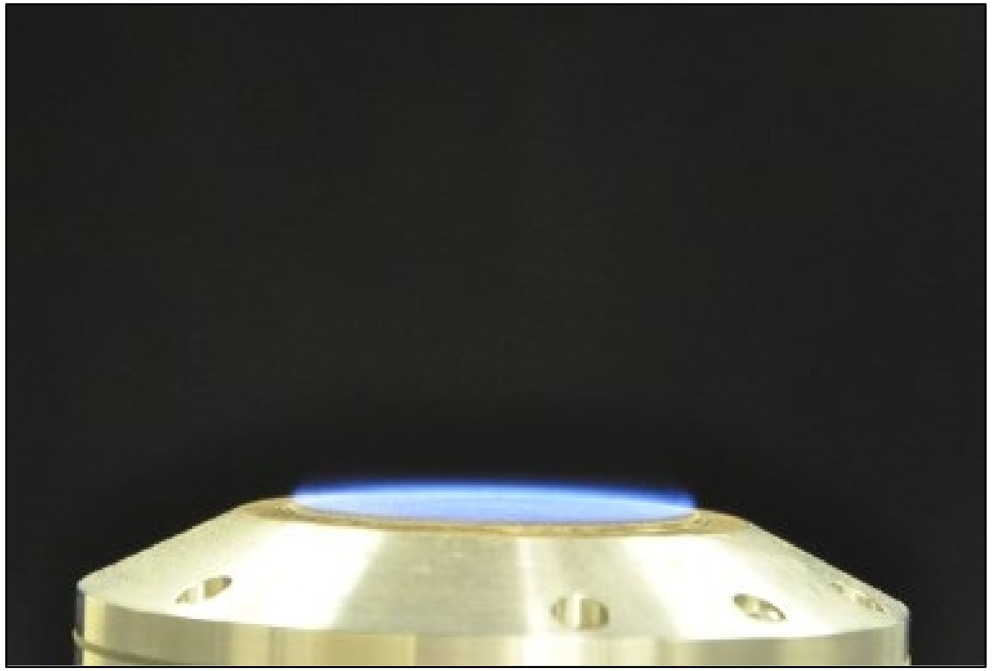
- **"McKenna" Burner**
  - **Laminar Premixed Flat Flame**



62.5mm

flatflame.com





Propane/Air

$\Phi = 1.0$

Analogous Combustion Reference Flame

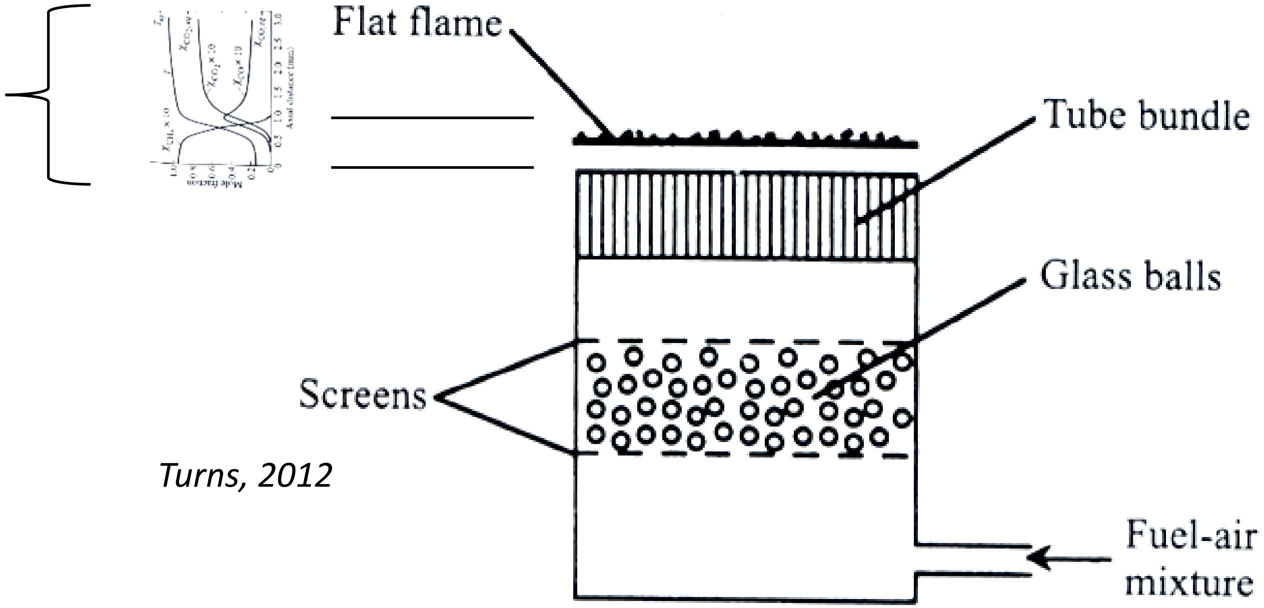
- **Methane/Air, Φ = 1.0**

Kinetic Calculations

Num	CH4	Air	CH4 Rotometer Setting	Air Rotometer Setting	Phi	T, adibatic	T, CARS
()	(slpm)	(slpm)	(mm)	(mm)	()	K	K
1	1.10	15.00	48	62	0.70	1338	1706
2	1.31	15.60	57	65	0.80	1997	1765
3	1.31	12.40	57	51	1.00	2226	1790
4	1.31	11.31	57	47	1.10	2211	1754
5	1.31	10.40	57	43	1.20	2137	1723
6	1.42	15.00	62	62	0.90	2134	1799
7	1.73	20.63	76	86	0.80	1997	1828
8	1.73	16.50	76	68	1.00	2226	1886
9	1.73	14.96	76	62	1.10	2211	1826
10	1.74	15.00	76	62	1.10	2211	1818
11	1.73	13.70	76	57	1.20	2137	1828
12	1.73	11.80	76	49	1.40	1980	1813
13	2.05	15.00	90	62	1.30	2057	1878
14	2.29	15.00	100	62	1.45	1942	1915
15	2.55	30.30	112	126	0.80	1997	1967
16	2.55	27.00	112	112	0.90	2134	1976
17	2.55	24.14	112	100	1.00	2226	2009
18	2.55	22.00	112	91	1.10	2211	1934
19	2.55	20.20	112	84	1.20	2137	1883
20	2.55	17.43	112	72	1.35	1980	1929
21	3.42	36.18	150	150	0.90	2134	2110
22	3.42	32.40	150	134	1.00	2226	2100

Mole fraction

Same F/A condition:
Same flame in
any lab, anywhere:
--Raman, CARS
--Laser Induced Incandescence
--Heat loss
--$US ~25,000



Turns, 2012

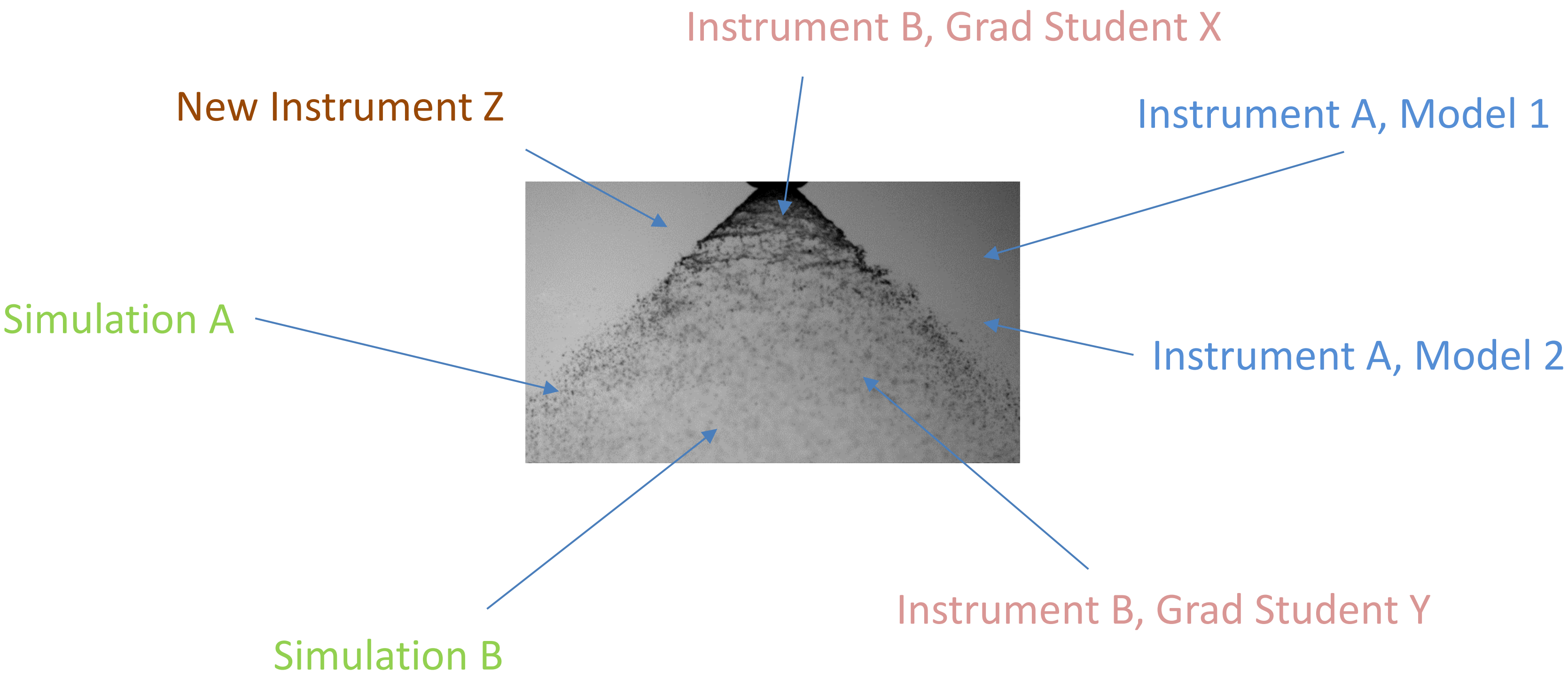
Perspective

- **The McKenna Burner has been an established reference flame for calibration and instrument assessment for ~40 years now**
  - **Temperature**
  - **Species**
  - **Soot**

Can the spray community embrace a similar concept for atomization and spray studies?

Perspective

- **Consideration of “Reference Sprays” as tools for aligning the spray community**



Reference Spray Allows Comparison in All Cases:
Instrument to Instrument, User to User, Simulation to Measurements, etc……

- **What could be simpler?**

Spanning the Applications

- **Examples of some atomizers used**

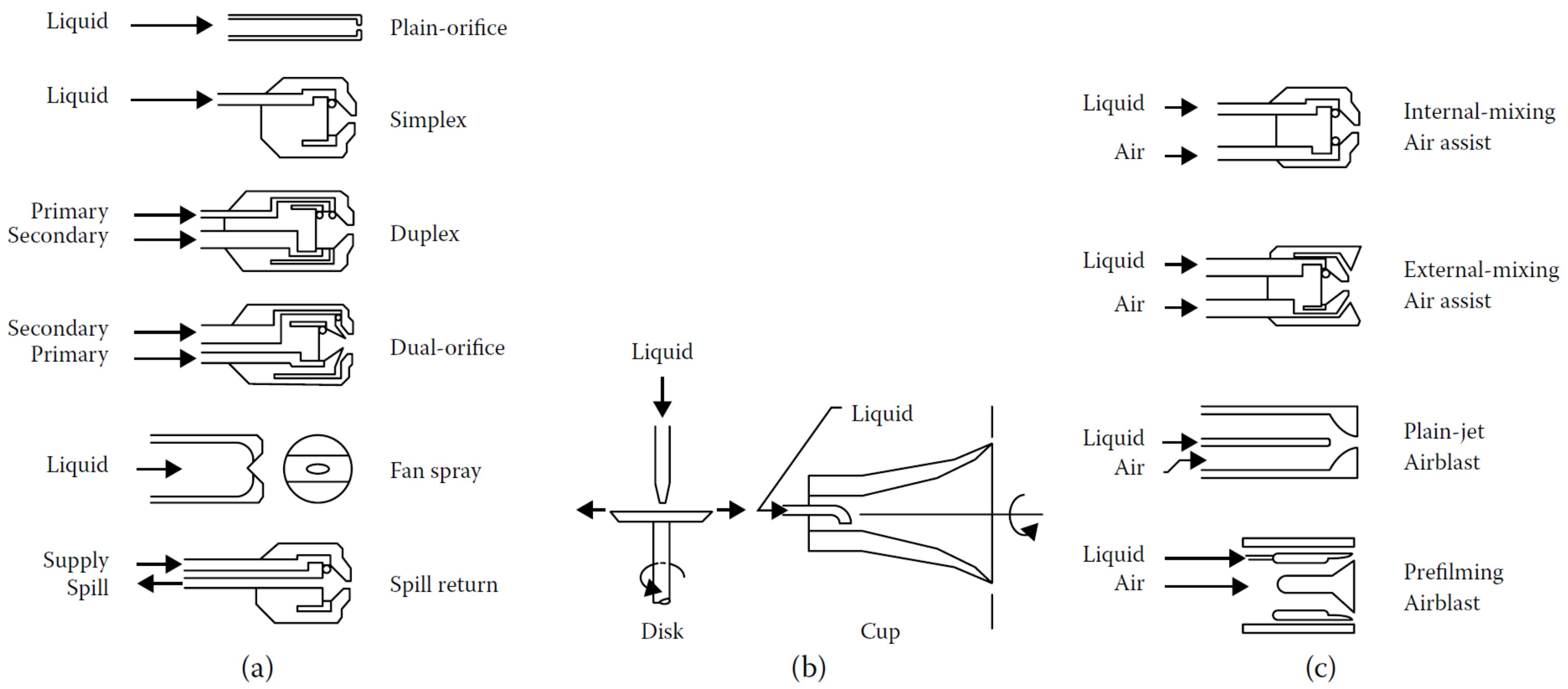


FIGURE 1.2
(a) Pressure atomizers, (b) rotary atomizers, and (c) twin-fluid atomizers.

Lefebvre and McDonell, 2017

Are there common underlying physics occurring among them?

Spanning the Applications

- Plain jet
- Simplex Atomizer
- Fan Spray

- Co-axial gas-liquid
- Plain jet in crossflow?
- Airblast

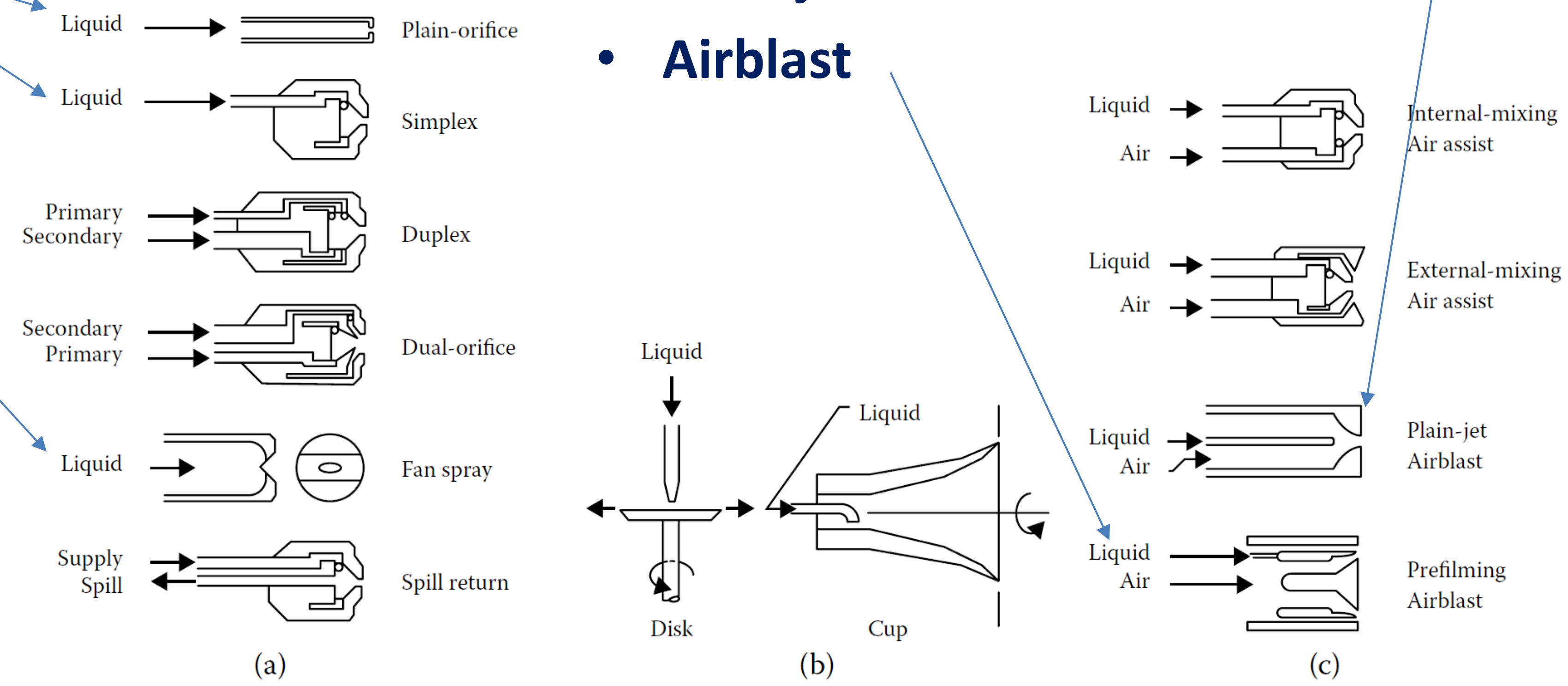


FIGURE 1.2
(a) Pressure atomizers, (b) rotary atomizers, and (c) twin-fluid atomizers.

Spanning the Applications

- **Plain jet**
- Simplex Atomizer
- Fan Spray
- Co-axial gas-liquid
- Plain jet in crossflow?
- Airblast

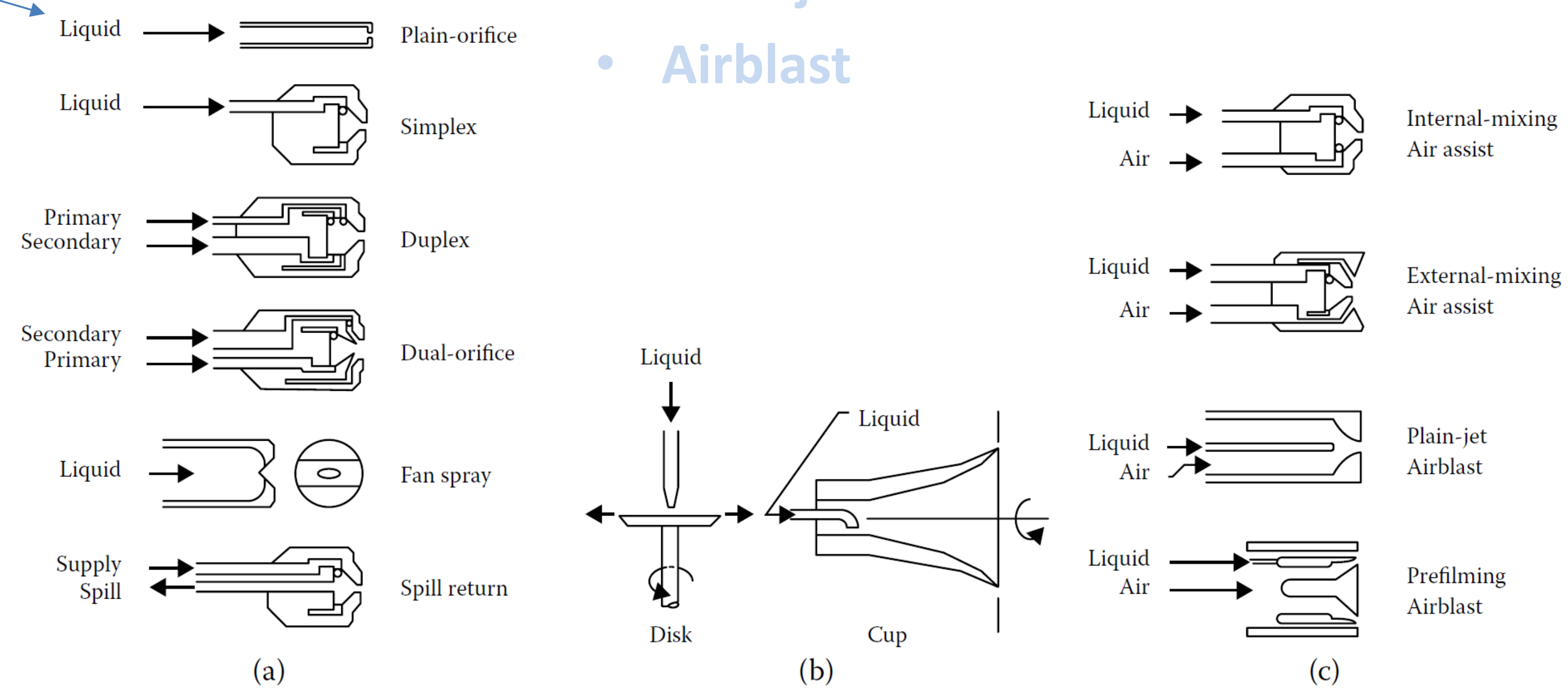
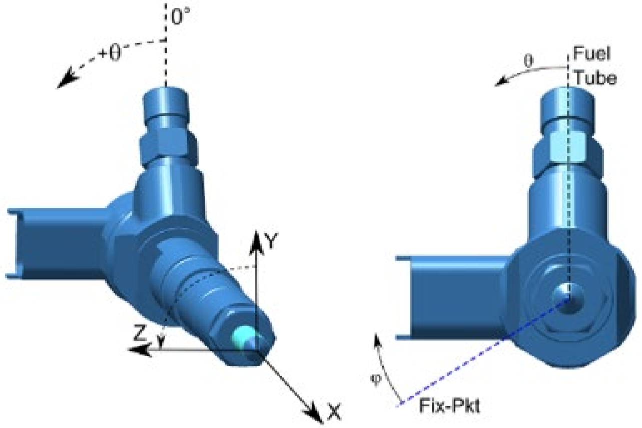


FIGURE 1.2
(a) Pressure atomizers, (b) rotary atomizers, and (c) twin-fluid atomizers.

Plain jet

- **High pressure conditions emulating diesel and GDI injector have been utilized extensively in the Engine Combustion Network (ECN)**
  - **https://ecn.sandia.gov/**



Bardi, M., Payri, R., Malbec, L.M., Bruneaux, G, Pickett, L.M., Manin, J., Bazyn, T., and Genzale, C. (2012). Engine Combustion Network: Comparison of Spray Development, Vaporization, and Combustion in Different Combustion Vessels, Atom & Spray, Vol 22(10), 807-842

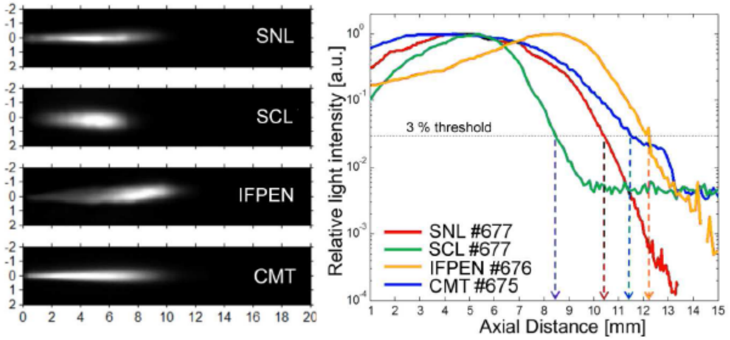
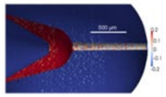


FIG. 3: Images obtained averaging the pictures acquired in the steady period of the injection from 800 to 1300 μs after the start of the injection (ASOI) (left). Intensity profile along the spray axis; the injector tip is at 0 mm on the X-axis (right).

Optical microscopy



X-ray tomography surface

X-ray phase contrast projection

Patterned after TNF (Turbulent Non-Premixed Flame Workshop
https://tnfworkshop.org/

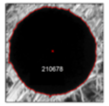
Plain Jet

- **ECN**
  - **Established mid 2000's**
    - ✓ **Several reference injectors (and associated Conditions) are available**
  - **Bosch provided injectors (diesel)**
    - ✓ **"Spray A"**
    - ✓ **"Spray B"**
    - ✓ **"Spray C"**
    - ✓ **"Spray D"**
  - **Delphi provided injectors (spray guided gasoline)**
    - ✓ **"Spray G"**
    - ✓ **"Spray M" multihole methanol**
  - **Evolving to include hydrogen and ammonia injection**

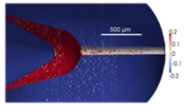
Plain Jet

- **e.g., Spray A**

Optical microscopy, x-ray tomography, and x-ray phase contra



Optical microscopy



X-ray tomography surface

Injector Serial #	Exit diameter [μm]	Exit boundary [μm]	θ [deg.]	Surface file .stl	Exit offset [μm]	Axial di [mm]
210370	90.8	B1	-90	stl	50	
210675	89.4	B1	9	stl*; stl	53	
210677	83.7	B1	32	stl	37	
210678	88.6	B1	36	stl	39	
210679	84.1	B1	-22	stl	22	

*Note 210675 tomography has been updated based on high-resolution x-ray tomography performed at CNRS, I which was recommended for computational grid generation for ECN3.

Below is a schematic of the definition used for the hole orientation. The orifice exit is located on the origin of the c the exit offset represent the location of the orifice with respect to the axis of the injector body and the fuel tube. N manufacturer. However, φ is referenced with two pins to hold the nozzle in position with respect to the injector bo reason, θ is defined as the angle between the fuel tube and the actual orifice in the counter clockwise direction wl the distance between the axis of the injector and the axis of the orifice at the exit.

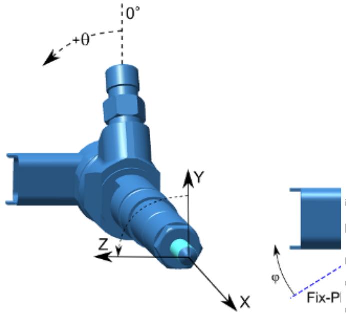


Fig. 6.3.1. Schematical definition for the orientation of the orifices for Spray A (axial single-hole nozzle).

Specifications for Spray A operating condition of the Engine Combustion Network[a]	
Ambient gas temperature	900 K **900 K**
Ambient gas pressure[b]	near 6.0 MPa **6 MPa**
Ambient gas density[b]	22.8 kg/m^3
Ambient gas oxygen (by volume)	15% O_2 (reacting); 0% O_2 (non-reacting). (look here for CO_2 and H_2O and N_2 %)
Ambient gas velocity	Near-quiescent, less than 1 m/s
Common rail fuel injector	Bosch solenoid-activated, generation 2.4
Fuel injector nominal nozzle outlet diameter	0.090 mm
Nozzle K factor	K = (d_{inlet} - d_{outlet})/10 [use μm] = 1.5
Nozzle shaping	Hydro-eroded
Mini-sac volume	0.2 mm^3
Discharge coefficient	C_d = 0.86, using 10 MPa pressure drop and diesel fuel
Number of holes	1 (single hole)
Orifice orientation	Axial (0&deg full included angle)
Fuel injection pressure	150 MPa (1500 bar), prior to start of injection
Fuel	n-dodecane[c]
Fuel temperature at nozzle[d]	363 K (90°C)
Common rail[e]	GM Part number 97303659. Used by 2005-2006 Duramax engines.
Common rail volume/length	22 cm^3/28 cm
Distance from injector inlet to common rail	24 cm
Tubing inside and outside diameters[f]	Inside: 2.4 mm. Outside: 6-6.4 mm.
Fuel pressure measurement	7 cm from injector inlet / 24 cm from nozzle
Injection duration	1.5 ms
Injection mass	3.5 – 3.7 mg
Approximate injector driver current	18 A for 0.45 ms ramp, 12 A for 0.345 ms hold
Access experimental data	Click for Spray A experimental data search

[a] from SAE Paper 2010-01-2106

[b] This exact combination of ambient pressure and density corresponds to a particular set of gases for a 0%-O2 condition with 89.71% N2, 6.52% CO2, and 3.77% H2O by volume and a compressibility factor, Z = 1.01. When different gases are used, the pressure must vary to maintain the same density

[c] Chosen as a fluorescence-free diagnostics fuel with known chemistry and properties. Other fuels may be selected after initial study and comparison.

[d] May be slightly different than injector body temperature

[e] Use rail outlet farthest away from fuel entrance (small orifice) to rail (i.e. cylinder #1).

[f] This 24 cm tube is available for purchase from USUI, reference part number IFP1. It is rated for 2500 bar.

Plain Jet

- **Spray A: Data Searching (http://ecn.sandia.gov/)**

DATA SEARCHING UTILITY

Simply click on values to narrow selection or choose from baseline searches. Results will be displayed after query yields less than 200 records.

Experimental Type	Ambient O_2 [%]	Ambient T [K]	Amb Dens [kg/m^3]	Inj Press *diff* [MPa]	Noz Diam [mm]	Serial Number	Fuel Type (description)	T_{Fuel} [K]	Inj Dur [ms]	Institution	Baseline Searches
ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	RESET SEARCH
Soot	0	900	22.8	150	Spray A	A210370	nC12	363	1.5	TU/e	Spray A
Lift-Off Length	13				0.090ks-a	A210675			4	cat	"Spray H" n-heptane
Ignition Delay	15					A210676			>4	cmt	1000K,42bar
Jet Penetration	21					A210677				ifpen	Soot vs Inj Press
F/A Mixture						A210678				sandia	Soot vs Ambient O_2
Velocity						A210679					Soot vs Orifice Diameter
Liquid Length											All Soot Measurements
High Speed Movie											

☑nominal ☑ambient ☑injector ☑experiment ☑add files ☐uncertainty ☐stand. dev ☐general ☐show empty

Click here for all header definitions - **Tabular data may be copied and pasted into delimited text or Excel file, or** download the entire .csv text-delimited file.

nO_2 [%]	nT_a [K]	$n\rho_a$ m^3	nOrif [mm]	nSernum	nInj P *diff* [MPa]	nInjdur D [ms]	nFuel Type	nFuel T_{fl} [K]	Institution	Readme	Refs	O_2	ambient composition	MW
15	900	22.8	0.090ks-a	A210677	150	1.5	nC12	363	sandia	readme	1 2	15	O2 = 15.00; N2 = 75.15; CO2 = 6.22; H2O = 3.62;	29.24
0	900	22.8	0.090ks-a	A210677	150	1.5	nC12	363	sandia	notes	1 2	0	O2 = 0.00; N2 = 89.71; CO2 = 6.52; H2O = 3.77;	28.68
15	900	22.8	0.090ks-a	A210676	150	1.5	nC12	363	ifpen	LO; IDSA; JP	1	15	O2 = 15.00; N2 = 71.73; CO2 = 1.71; H2O = 11.56;	27.72
0	900	22.8	0.090ks-a	A210676	150	1.5	nC12	363	ifpen	LLSA; JP	1	0	O2 = 0.00; N2 = 87.01; CO2 = 1.68; H2O = 11.32;	25.89

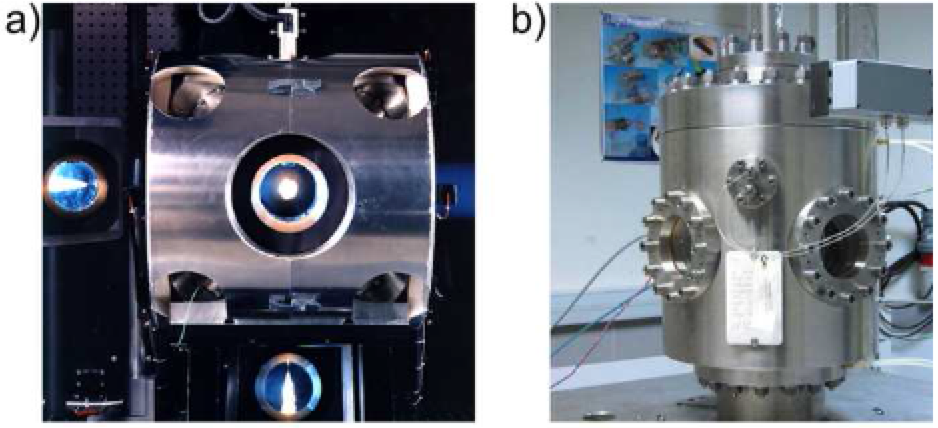
nO_2 [%]	T_a [K]	Ta_ai	T_{Bulk} [K]	ρ_a [kg/m^3]	ρ_a aft ign	ρ_{Bulk} [kg/m^3]	Amb P [MPa]	Z	amb v	amb v_{Turb}	vess Geom	actual injP	T_{fuel}	T_{noz}	roi
15	889.2; Temp Distr	889.3	827.3	23.06	23.07	24.78	5.92	1.015	0.2	-	Vesssel Geometry	151.2;fuel pressure vs time	373	Meijer 2012	rate of injection
0	891.9; Temp Distr	-	829.5	23.01	-	24.74	6.05	1.016	0.2	-	Vesssel Geometry	152.7;fuelPvsTime	373	Meijer 2012	rate of injection
15	891.4	894.2	845.2	22.28	22.28	23.5	6.01	1.01	1	-	Vesssel Geometry	157.4;fuel pressure vs time	-	363	-
0	887.9	-	841.9	22.28	22.28	23.5	6.12	1.01	1	-	Vesssel Geometry	158.4;fuel pressure vs time	-	363	-

Work it may, but *SHINE* it must.
Last modified on July 25, 2019
Your query took 0.022890 seconds

Sandia National Laboratories

Plain Jet

- **Spray A: Example Results—Effect of Chamber & Diagnostic on Penetration**



Institution	Facility	Nozzle #
SNL	CVP	210677
SCL	CPF	210677 / 210678
CMT	CPF	210675
IFPEN	CVP	210676

FIG. 1: Global view of the spray combustion chambers: (a) a constant-volume preburn (CVP) test chamber (SNL) and (b) a constant-pressure flow (CPF) vessel (CMT).

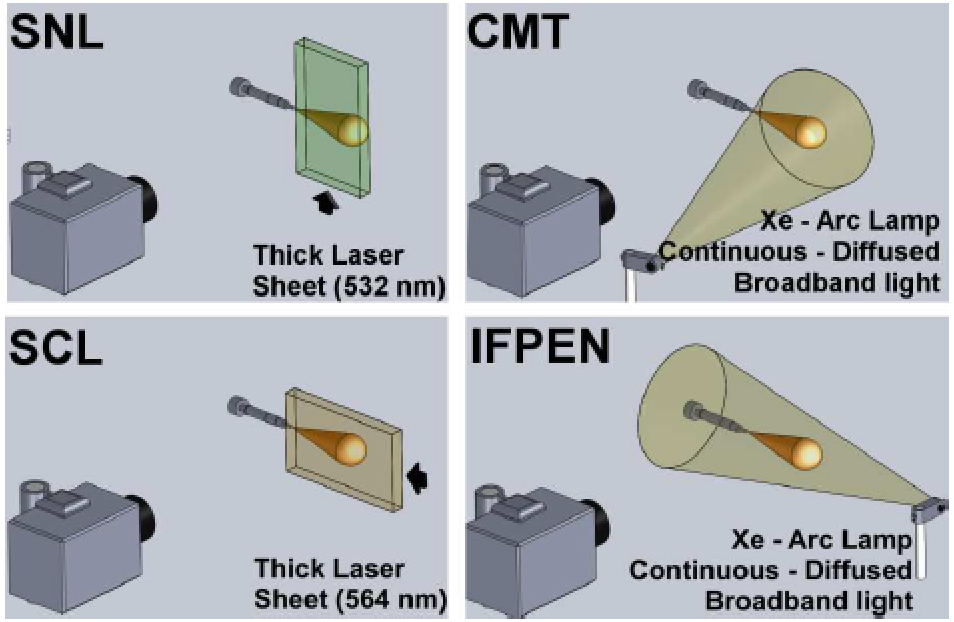
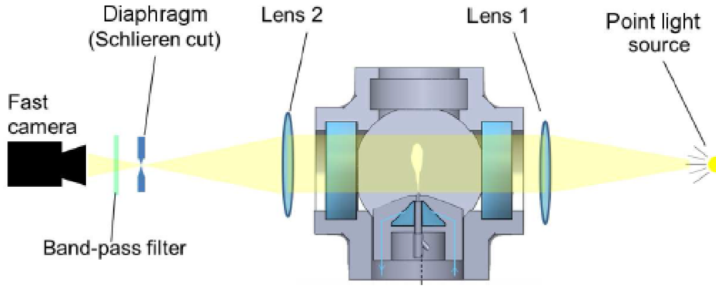


FIG. 2: Schematic of the Mie scattering setup for liquid length penetration and details of the solutions employed by each institution.

Bardi, M., Payri, R., Malbec, L.M., Bruneaux, G, Pickett, L.M., Manin, J., Bazyn, T., and Genzale, C. (2012). Engine Combustion Network: Comparison of Spray Development, Vaporization, and Combustion in Different Combustion Vessels, Atom & Spray, Vol 22(10), 807-842

- **Spray A: Example Results—Effect of Chamber & Diagnostic on Penetration**



	Light source	Focal Length		Diaphragm (schlieren cut)	Filter	Camera lens
		Lens 1	Lens 2			
CMT	Xe-arc continuous	Parabolic mirror –750 mm	450 mm	6 mm	no	50 mm f/1.8
IFPEN	He-Ne laser (632 nm) continuous	600 mm	600 mm	dark field 17 mm disc	BPF cwl: 632 nm	50 mm f/1.8
SCL	Cu Laser (580 nm) pulsed	450 mm	450 mm	no	BPF cwl: 580 nm	50 mm f/1.8
SNL	Blue LED (460 nm) continuous	Parabolic mirror –915 mm	Parabolic mirror –915 mm	no	BPF cwl: 430 nm	50 mm f/1.2

FIG. 5: Sketch of the setup employed for vapor-phase penetration measurements (top). Summary of the optical configurations used by the institutions (bottom).

Bardi, M., Payri, R., Malbec, L.M., Bruneaux, G, Pickett, L.M., Manin, J., Bazyn, T., and Genzale, C. (2012). Engine Combustion Network: Comparison of Spray Development, Vaporization, and Combustion in Different Combustion Vessels, Atom & Spray, Vol 22(10), 807-842

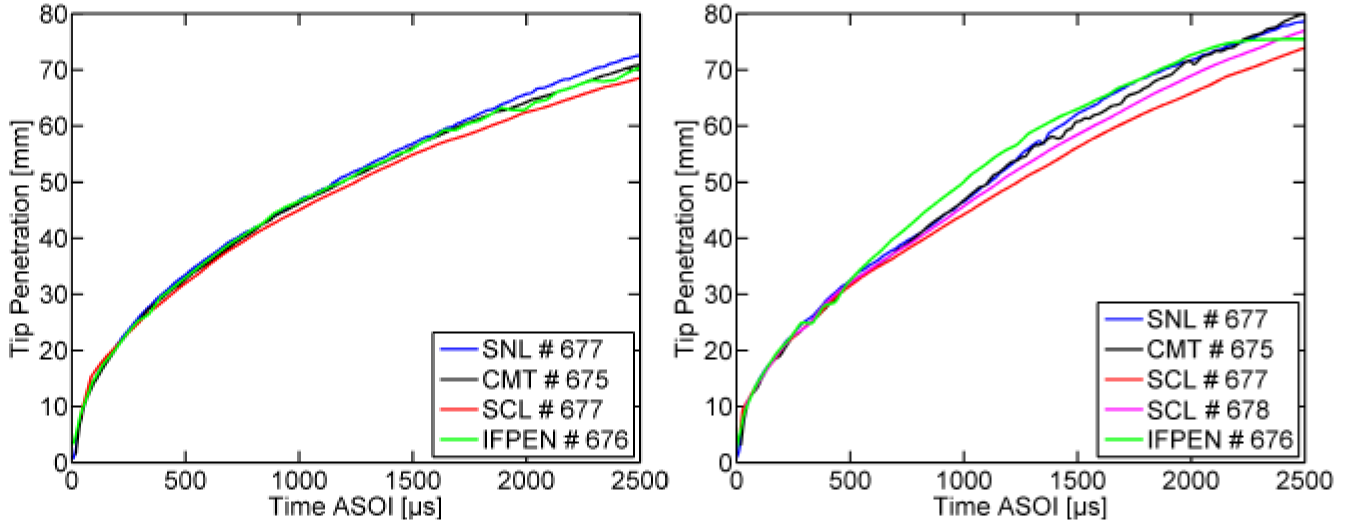
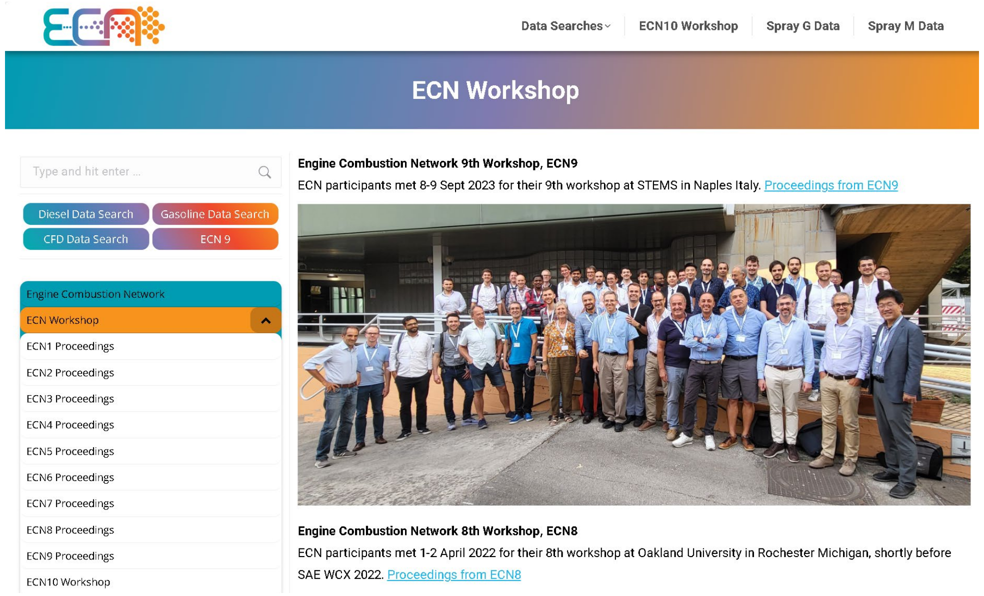


FIG. 7: Vapor-phase penetration measured in the different institutions in inert (left) and reacting (right) conditions.

Plain Jet

- **Summary**
  - **Engine Combustion Network**
    - ✓ Remarkable example of use of reference sprays
    - ✓ Widely used in practice
      - – Large number of publications associated with the program
      - – 9 Workshops held
        - » All presentations from prior ECN workshops are available (audio/video presentations)
    - ✓ Some limitations associated with need for appropriate test chambers/conditions
      - – Conditions and facility are as critical as the injector itself
        - » Limited to institutes with such capability
    - ✓ "All injectors are not created equally"



Pressure Swirl Atomizer

- Plain jet
- **Simplex Atomizer**
- Fan Spray

- Co-axial gas-liquid
- Plain jet in crossflow?
- Airblast

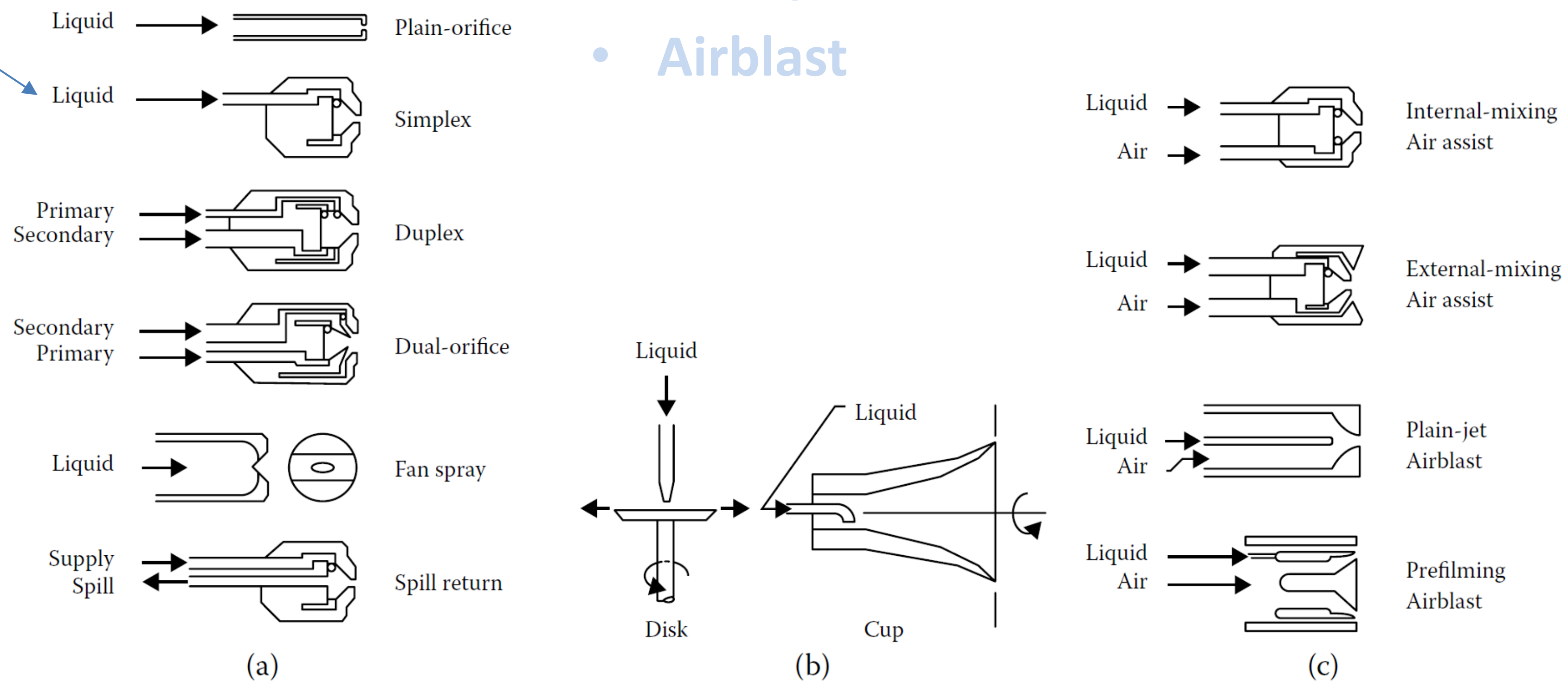
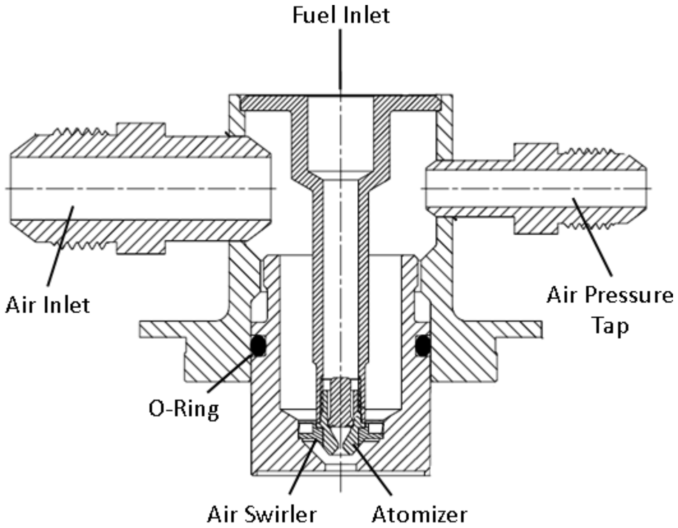


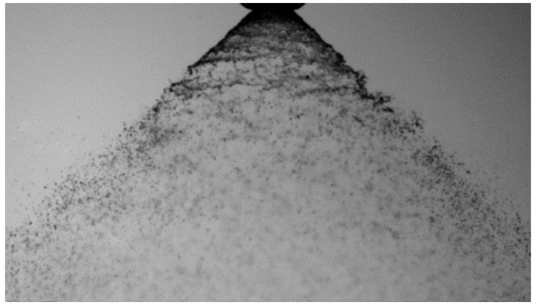
FIGURE 1.2
(a) Pressure atomizers, (b) rotary atomizers, and (c) twin-fluid atomizers.

Consider inspiration and leadership for Aerospace and Propulsion TC

Pressure Swirl Atomizer

- **Concept of a "Research Simplex Atomizer" was developed in 1980's by Parker Hannifin (Simmons) for a "round robin" exercise inspired be Lee Dodge (SwRI)**





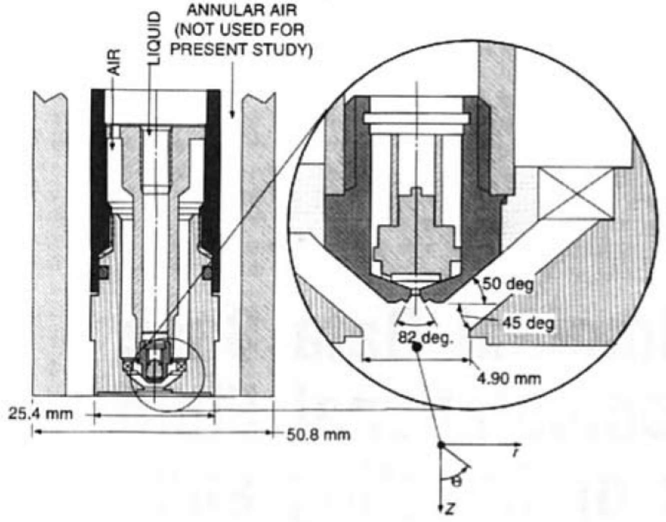


Fig. 1 Research simplex atomizer

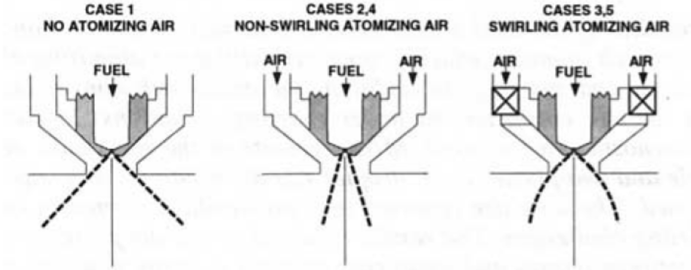


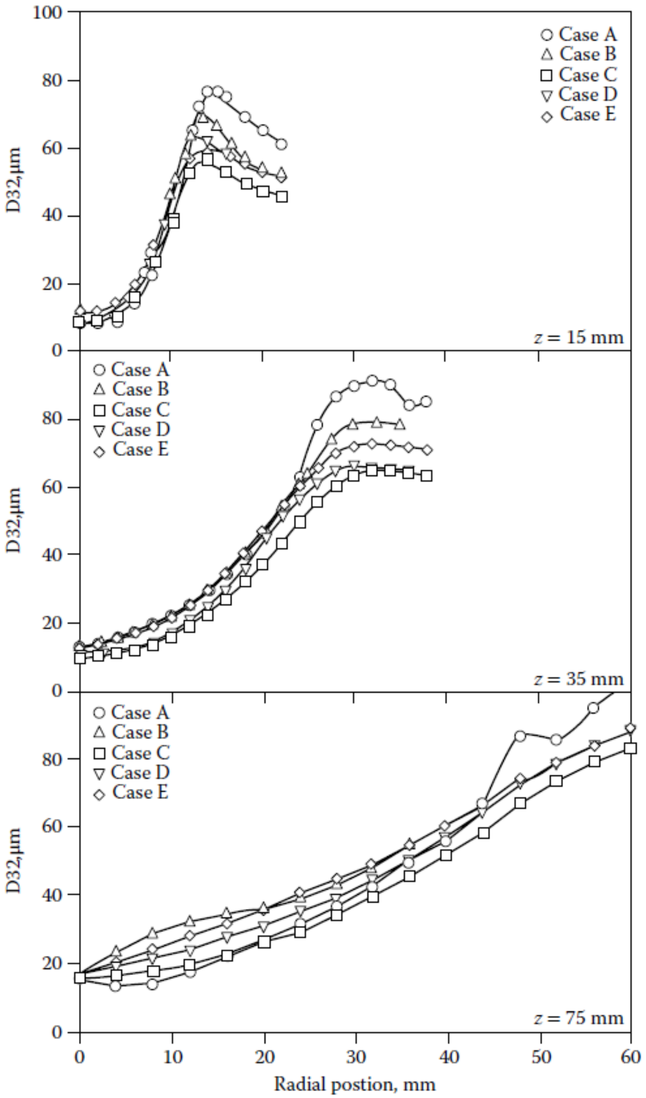
Fig. 2 Three modes of injection

McDonell, V. G., Samuelsen, G. S. (1995). An Experimental Database for the Computationnel Fluid Dynamics of Reacting and Nonreacting Methanol Sprays, ASME J. Fluids Engineering, Vol 117, pp 145-154

Pressure Swirl Atomizer

Previous “RSA” Work

- **Investigation of results from multiple laboratories and instruments**
  - Dodge et al. (1987) looked at fifteen laboratories and seventeen instruments for droplet sizing of two pressure-swirl atomizers, including one dubbed “Research Simplex Atomizer”
    - ✓ Large variation in data, partly due to different instrumentation design from different models
    - ✓ Calibrated laser diffraction systems had most consistency
  - Research Simplex Atomizer (RSA) tested across two laboratories (UCI/NCKU)→
  - NASA and NIST also used same RSA: different conditions



Dodge, L. G., Applied Optics 26-7: 1328-1341 (1987).
McDonell, V. G., Samuelsen, G. S., Wang, M. R., Hong, C. H. and Lai, W. H., Journal of Propulsion and Power 10-3: 402-409 (1994).

Pressure Swirl Atomizer

Previous Work

- **Datasets**
  - UC Irvine (McDonell)=>
  - NIST (Presser)
  - NASA (Bulzan)

- **Myriad of simulation studies**

- **Example of a "Target Data Set"**

Table 3
Summary of modeling studies of the UC Irvine methanol spray experiments (McDonell and Samuelsen [173]).

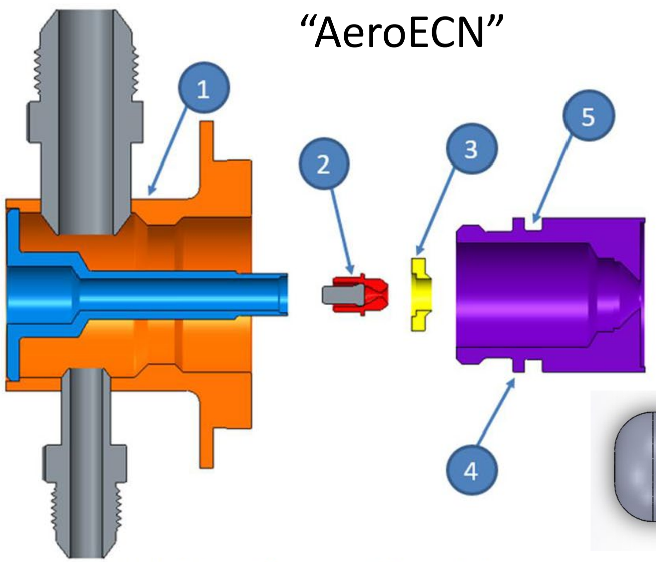
Case	Simulation	Model	Remarks
Non-reacting Non-swirling	Raju 2002 [214]	k-ε Transported scalar PDF	Small difference between PDF model and model neglecting fluctuations
Reacting Non-swirling	Raju 2002 [214]	k-ε Transported scalar PDF Reduced chemistry	Large difference between PDF model and model neglecting fluctuations
Reacting Non-swirling	Hollman and Gutheil 1996 [115]	k-ε Assumed PDF Laminar Flamelet	Ignition criterion added
Reacting Non-swirling	Hollmann and Gutheil 1998 [116]	k-ε Assumed PDF Spray flamelet model	Validation of new assumed shape Ignition criterion not needed
Nonreacting Non-swirling	Ge and Gutheil 2006 [92]	k-ε Mixture fraction Assumed PDF and Transported PDF	Comparison of PDF methods Validation of modified assumed PDF
Reacting Non-swirling	Ge and Gutheil 2008 [90,93]	k-ε Hybrid RANS-PDF 2-scalar PDF Spray flamelet	Joint statistics Mixture fraction and enthalpy Extended IEM micro-mixing
Non-reacting Swirling	De Meester 2012 [62]	Velocity-composition Transported PDF Lagrangian–Lagrangian	Comparison of vapor distribution models
Reacting Swirling	De Meester 2012 [62]	Velocity-composition Transported PDF Flamelet/REDIM Lagrangian–Lagrangian	Comparison of flamelet and REDIM chemistry and of seen composition models

Jenny, Roekaerts, and Beishuizen (2012). *Prog Energy Comb Sci.*, Vol 38, 846-887

Pressure Swirl Atomizer

- Original “RSA” continued to be offered for $US 6,000 to interested parties until ~2000
- Original “RSA” no longer supported or even able to be built
- In 2017, the concept was resurrected using similar design but with current fabrication methods and new support from Advanced Atomization Technologies (AAT)

“AeroECN”



The atomizer unit consists of 6 separable components:

1. Body
2. Atomizer
3. Air swirler (optional configuration)
4. Tip
5. O-ring
6. Gasket (not pictured)

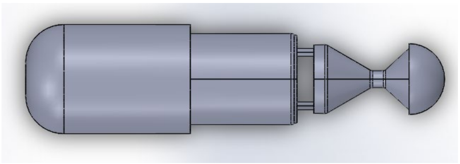
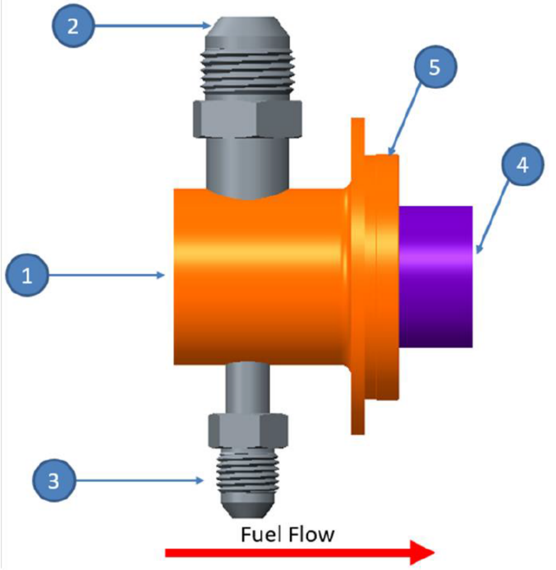


Figure 4: Exploded assembly review of the standard atomizer.

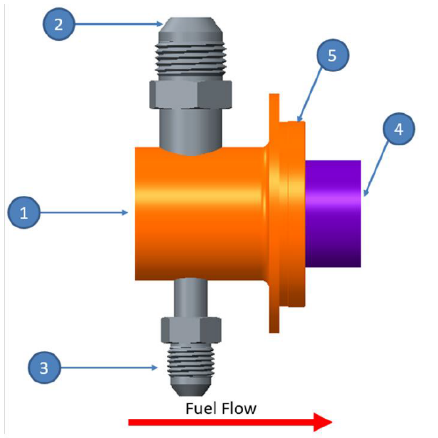
Thistle, A., Hall, B., and McDonell, V. (2018). Standard Simplex Atomizer Program Status and Expectations, ICLASS 2018, Chicago, July



1) Fuel inlet:
   1/8” NPT
2) Air Inlet:
   #8 37° JIC Fitting
3) Air pressure tap:
   #5 37° JIC Fitting
4) Nozzle exit
5) 2.000-20 UN-2A thread

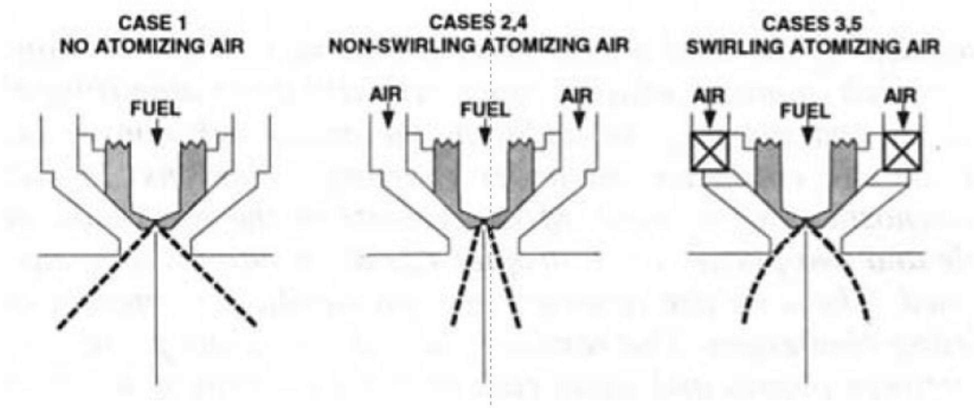
Pressure Swirl Atomizer

- **Test Conditions ***
  - **Goal: Conditions most any lab/institute can attain**
    - ✓ **No need for specialized equipment or exhausting**
  - **Nominally "quiescent" environment**



1) Fuel inlet:
   1/8" NPT
2) Air Inlet:
   #8 37° JIC Fitting
3) Air pressure tap:
   #5 37° JIC Fitting
4) Nozzle exit
5) 2.000-20 UN-2A thread

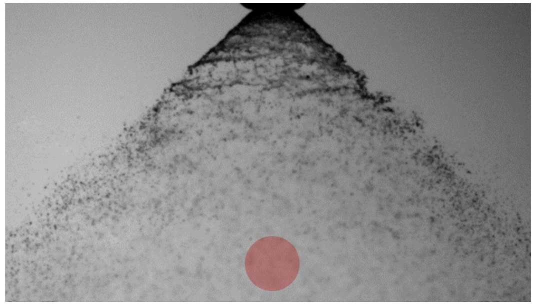
- **Initial Injector Conditions/Measurement Locations***
  - **25, 50, 100 psi**
  - **Water, Methanol,**
    Mil-PRF-7042 Type II Calibration Fluid
  - **Z = 25, 50, 100 mm**



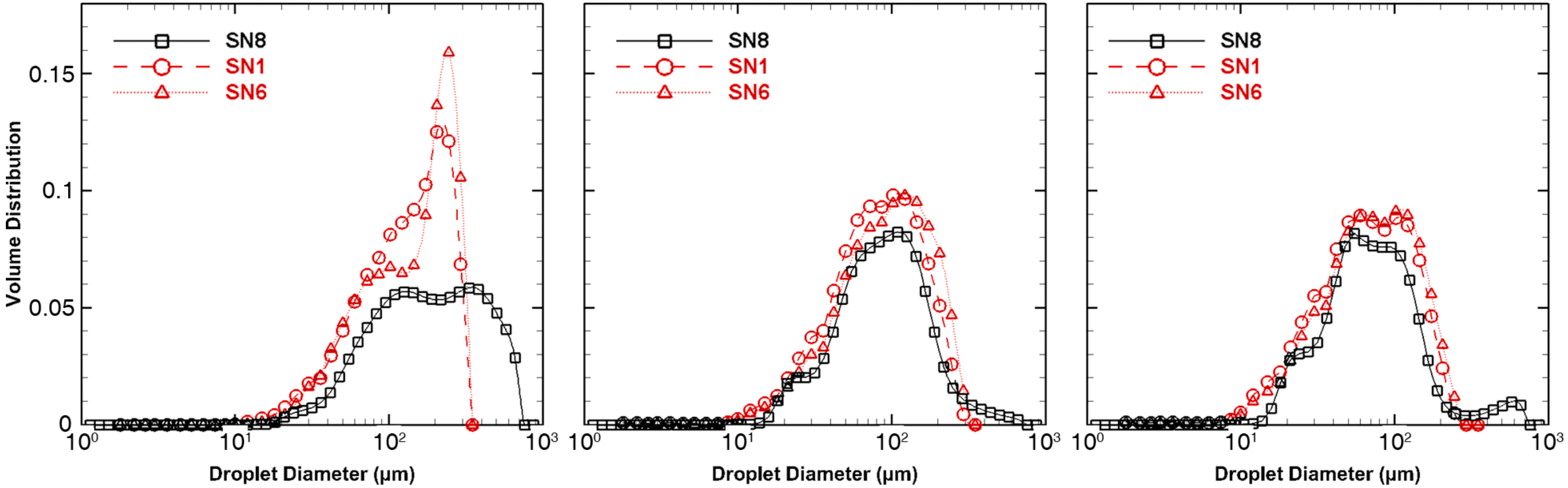
- **Options for air-blast operations are "built in" used by UCI, NASA, NIST on original**

*No real consensus yet

Pressure Swirl Atomizer



- **Example: Multilab Laser Diffraction of MIL-PRF-7024**
  - **2 inches downstream of the centerline**
  - **25 psi, 50 psi, and 100 psi**
  - **Different optical setups, operators, and RSA models were used**
  - **Measurable range must equal spray range**

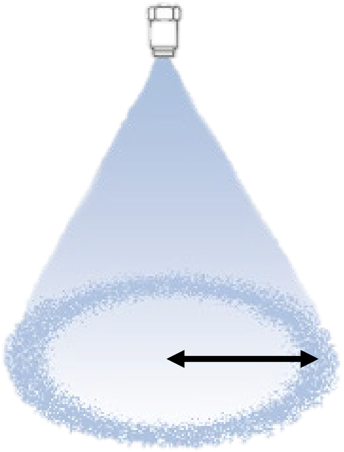


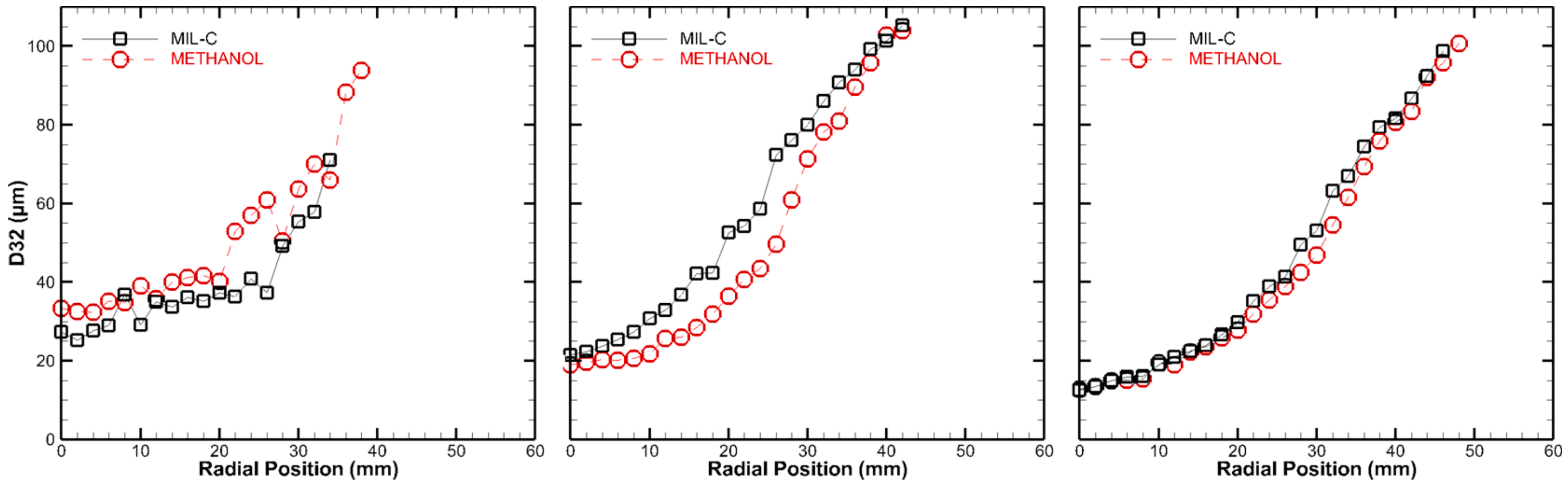
25 psi 50 psi 100 psi

Leask, S.B., Li, A.K., McDonell, V., and Samuelsen, G.S. (2018). Evaluation of Research Simplex Atomizers and a Measurement Standard, ICLASS 2018, Chicago, July
Leask, S.B., Li, A.K., McDonell, V., and Samuelsen, G.S. (2019). Preliminary Development of a Measurement Reference Using a Research Simplex Atomizer, ASME Journal of Fluids Engineering, Vol 141

Pressure Swirl Atomizer

- **Example: Impact of Test Liquid Type**
  - **Phase Doppler point measurements**
  - **MIL-PRF-7024 Type II ("Mil-C) and methanol**
  - **Less effect of physical properties as pressure increases**





25 psi 50 psi 100 psi

Leask, S.B., Li, A.K., McDonell, V., and Samuelsen, G.S. (2018). Evaluation of Research Simplex Atomizers and a Measurement Standard, ICLASS 2018, Chicago, July
Leask, S.B., Li, A.K., McDonell, V., and Samuelsen, G.S. (2019). Preliminary Development of a Measurement Reference Using a Research Simplex Atomizer, ASME Journal of Fluids Engineering, Vol 141

Pressure Swirl Atomizer

- **Example: Instrument Comparison**
  - **Phase Doppler vs X-Ray (SN5: same orientation)**
  - **Mass per Volume space**

10 mm downstream

0.2 mm downstream

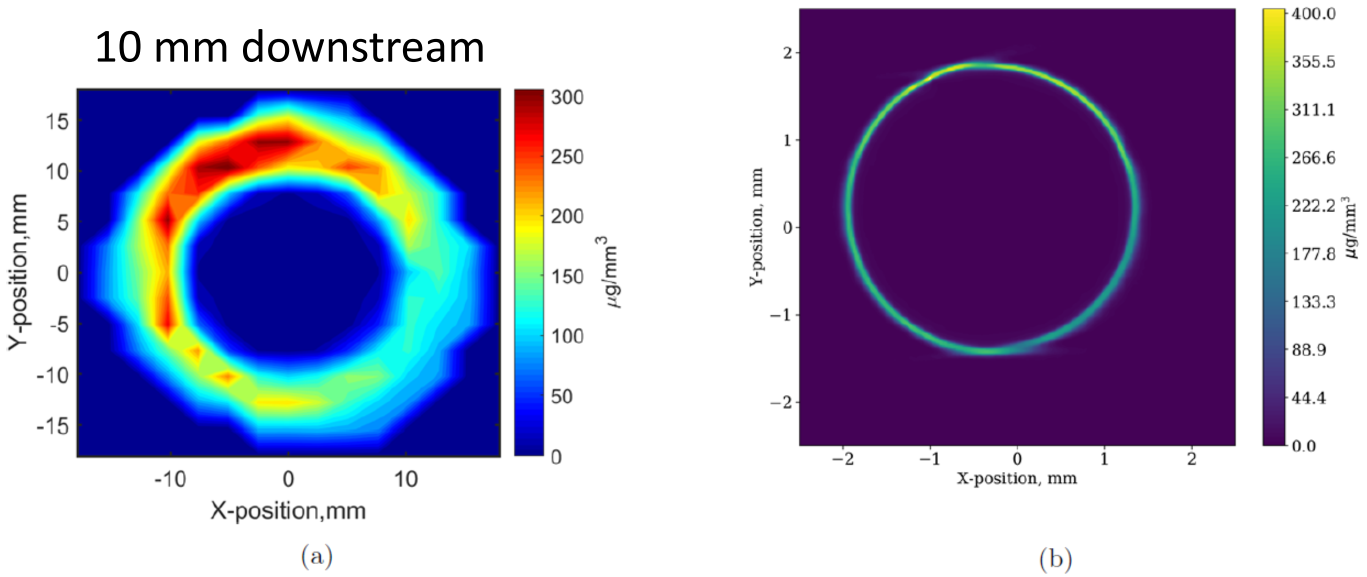
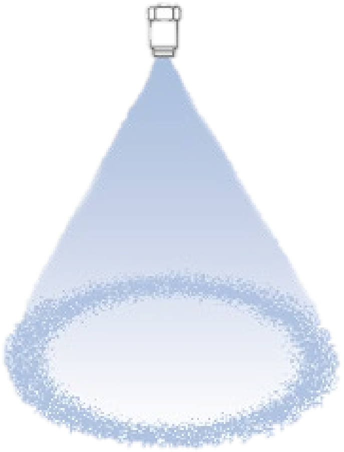
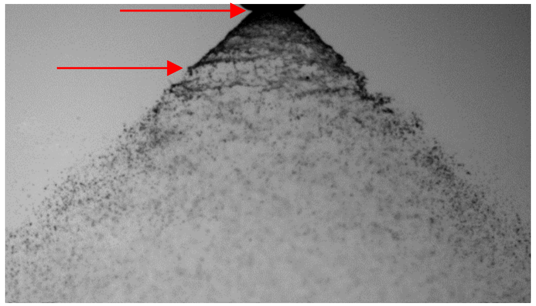


Figure 3: Mass per volume distribution for SN5 at 100psig for (a) PDI and (b) X-ray.

UC Irvine

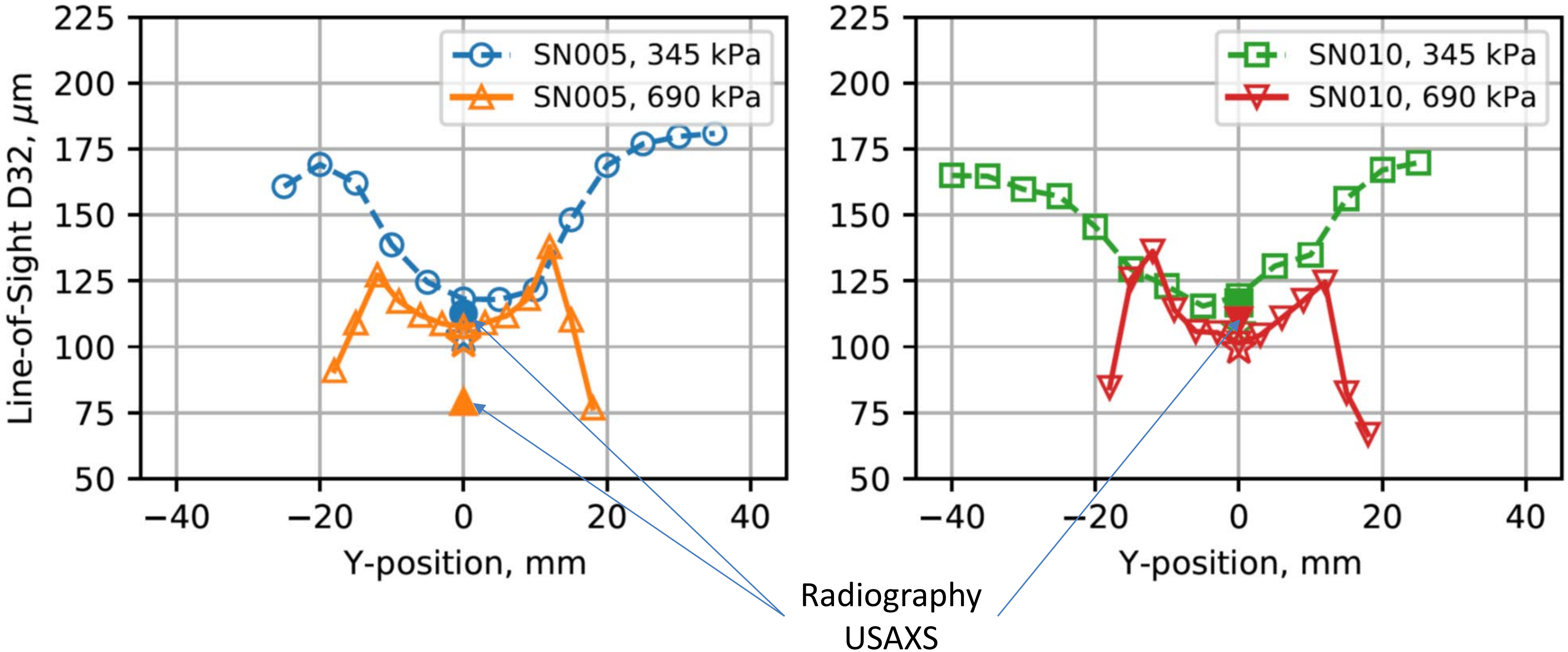
Argonne Nat'l Lab





Sforzo, B., Leask, S.B., Li, A.K., Tekawade, A., Powell, C.F., McDonell, V.G., and Kastengren, A.L. (2019). Complementary Characterization of Standard Simplex Atomizers using Phase Doppler Interferometry and X-Ray Radiography, ILASS 2019, Tempe AZ, May

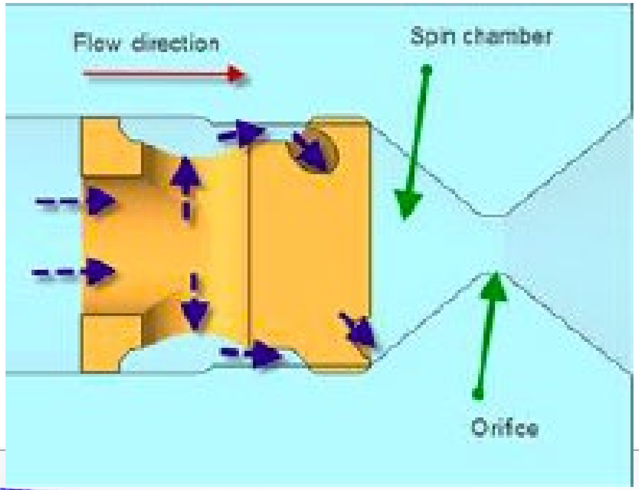
- **Example: Instrument Comparison**
  - **PDI vs USAXS D32**

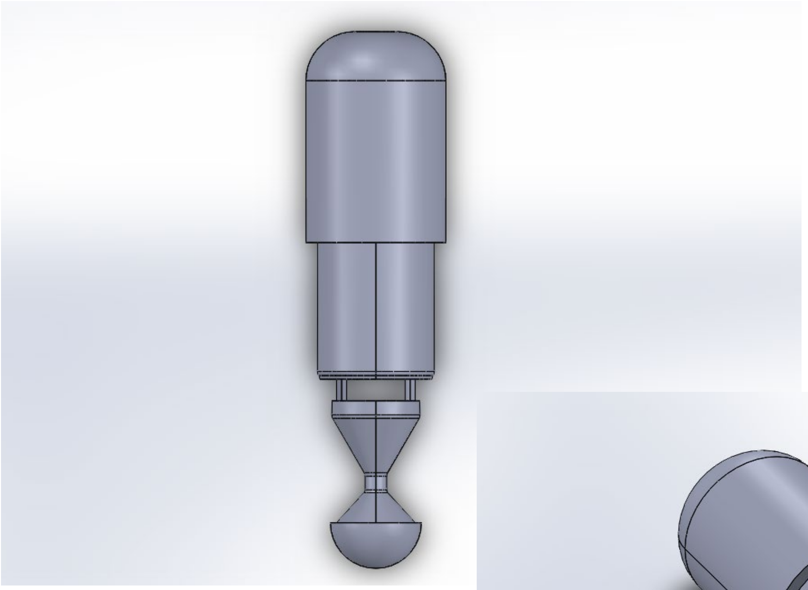


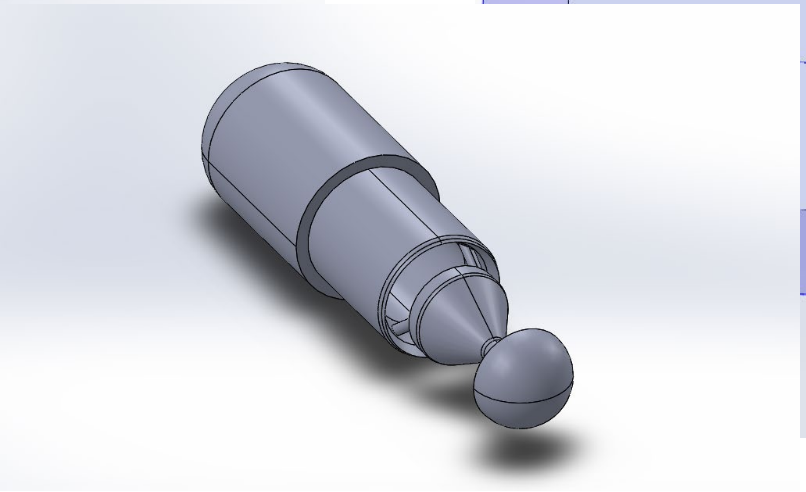
Sforzo, Kastengren, Ilavsky, Powell, Leask, McDonell (2021). Application of Phase Doppler Interferometry and Ultra Small Angle X-Ray Scattering to the Near Field Spray from a Reference Simplex Atomizer, ICLASS 2021

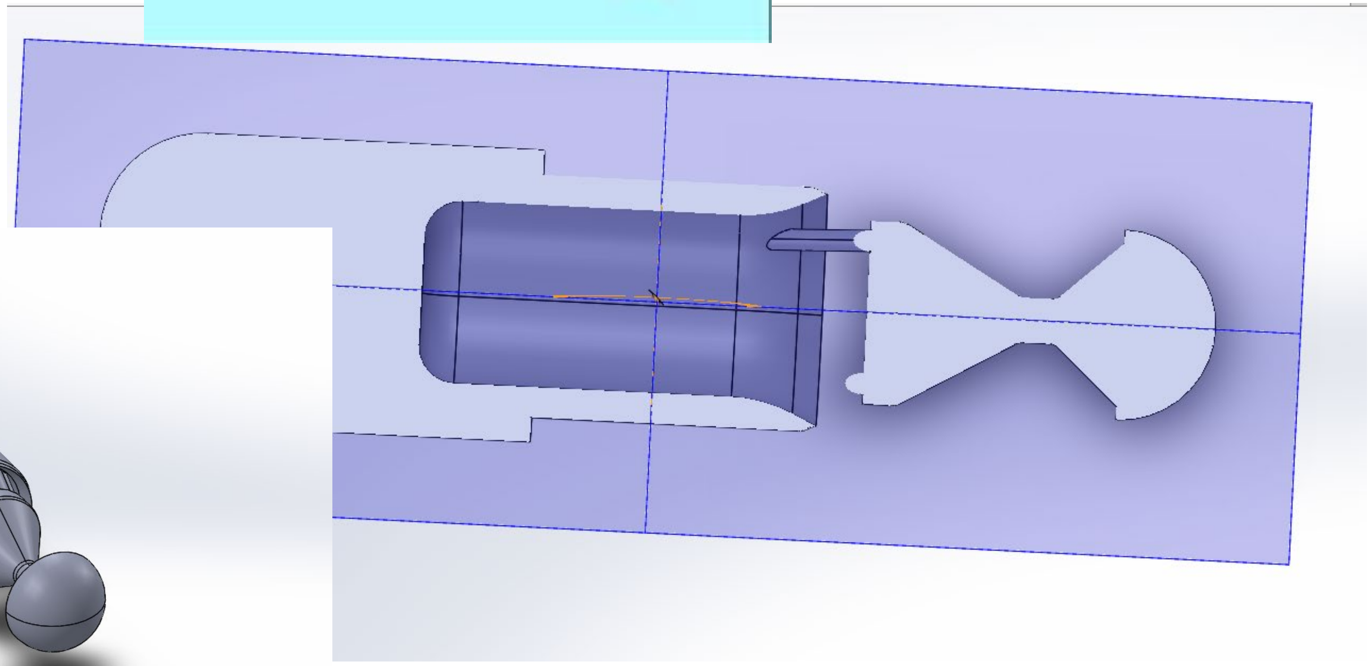
Pressure Swirl Atomizer

- **CAD files available**
  - **Interior fluid "container"**





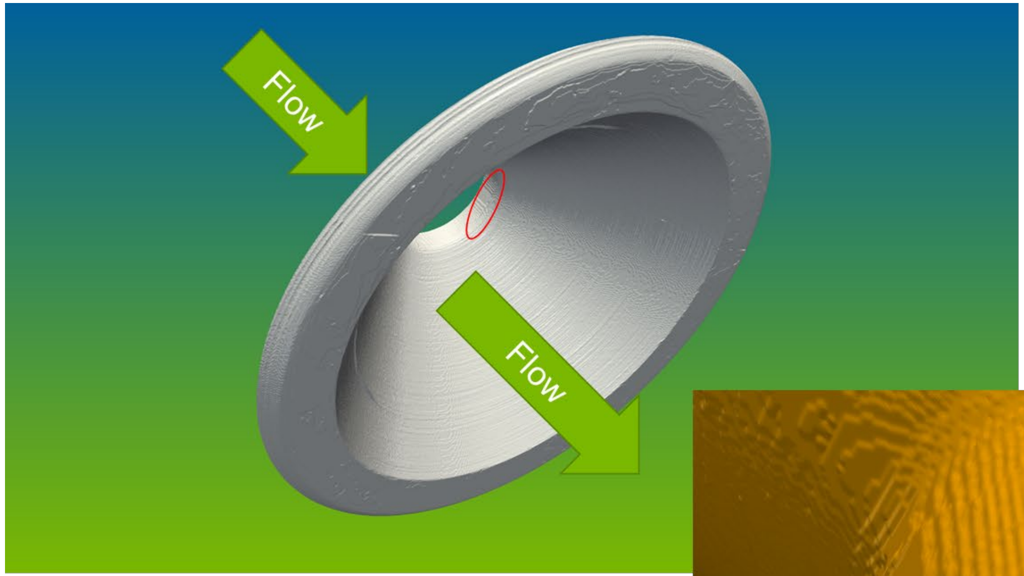


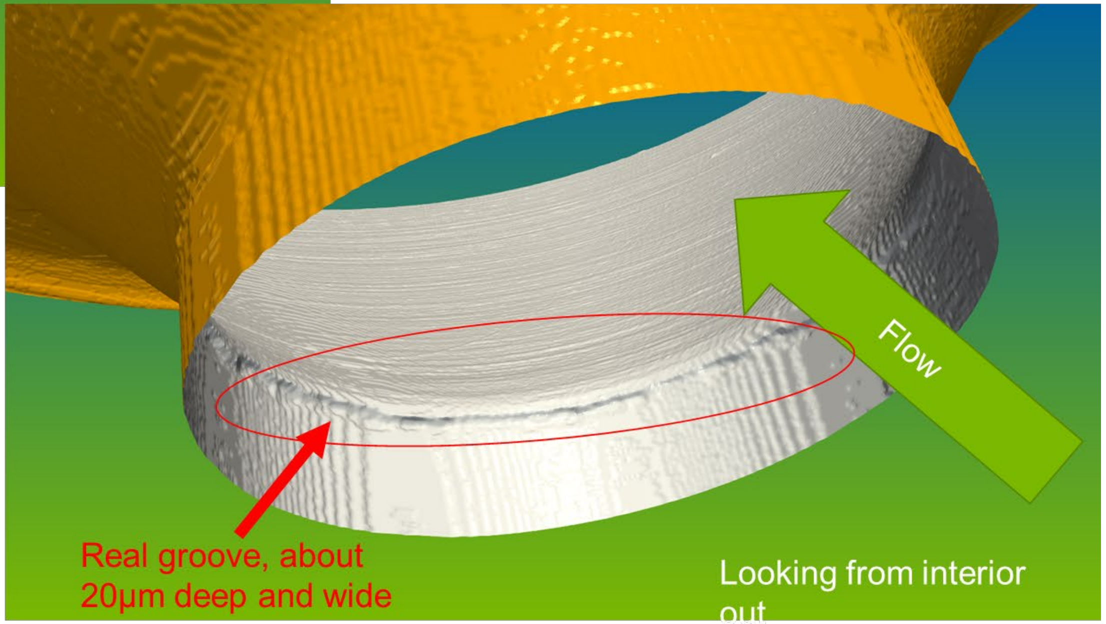


Actual Interior Geometry ("CT Informed")

- **Argonne National Lab (SN 5)**

Sforzo, Tekawade, Kastengren, Powell, Leask, Li, and McDonell (2020). Geometry and spray characteristics of standard somplex sprays, AIAA SciTech 2020, Orlando, FL





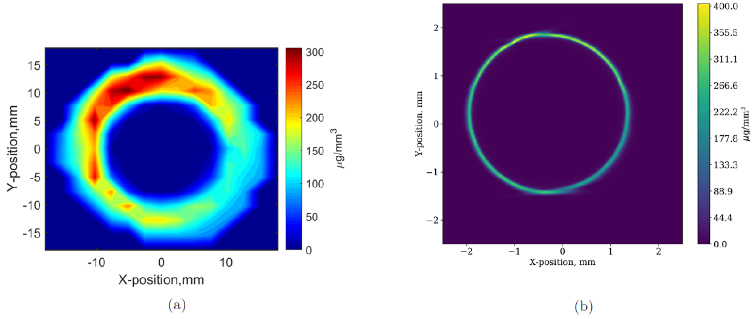


Figure 3: Mass per volume distribution for SN5 at 100psig for (a) PDI and (b) X-ray.

Parallel Simulation Efforts Underway…..

- Univ of Montana (M. Owkes)
- CMT Motores Termicos (R. Payri)
- University of Massachusetts—Lowell (N. van Dam)
- Convergent Science (G. Jacobsohn*)
- ……

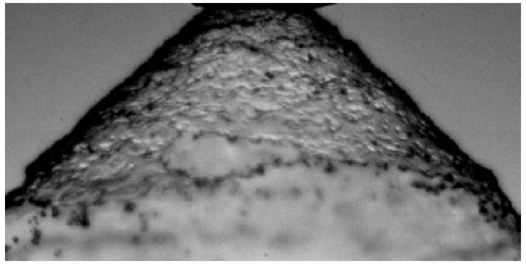


Fig. 5 Visual light image, SN05 atomizer operating at 100 psig injection pressure. The image extends approximately 7 mm of downstream of the injector tip.

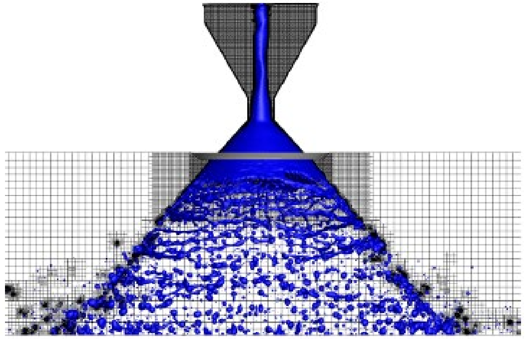
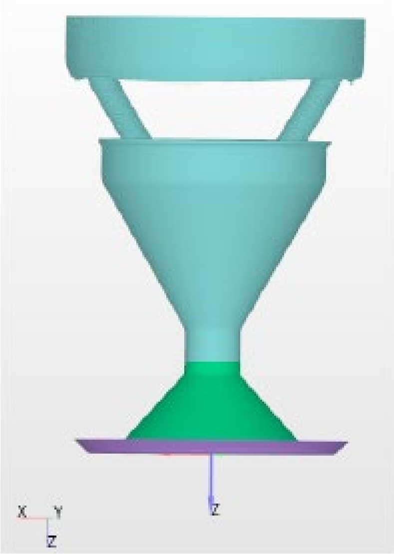
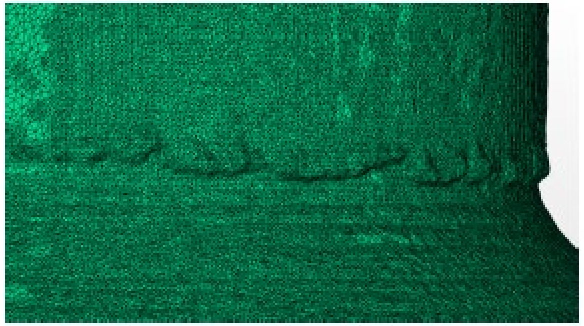


Fig. 6 Iso-surface of $\alpha = 0.75$ for simulation using SN05 atomizer geometry, 100 psig nominal injection pressure. Image captures the full downstream extend of the CFD domain, 5 mm downstream of the injector tip.





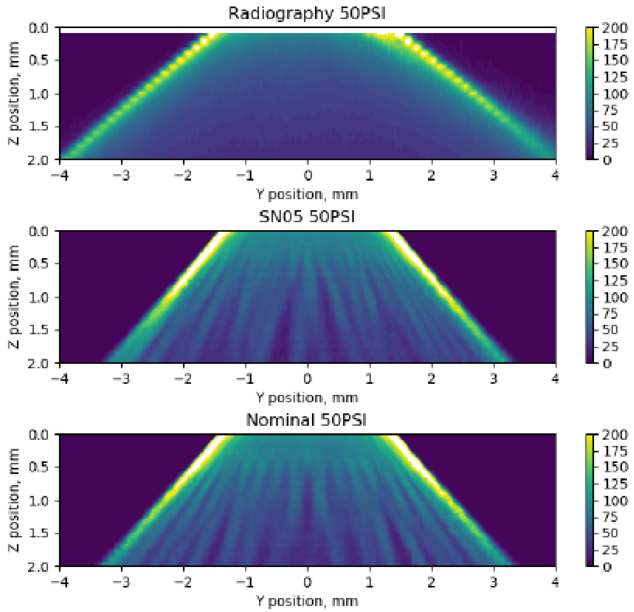


Fig. 2 SN05 x-ray iso-surface used as CFD geometry (left) and detail view (right).

Jacobsohn, Sforzo, Kastengren, Tekawade, Powell, Leask, Li, and McDonell (2021). An experimental and numerical investigation of research simplex atomizer sprays, AIAA SciTech 2021, Virtual

Pressure Swirl Atomizer

- **With Heritage of Legacy RSA, "RSA II" or "AeroECN" now available**
- **Contact Ethan Hanson of AAT**
- **Snapshot from several years ago…..**

S/N	Institution	Owner	Owner contact
AECN-A001	En'Urga	Sivathanu	Yudaya Sivathanu <sivathan@enurga.com>
AECN-A002	AAT	Hanson	
AECN-A003	AAT	Hanson	
AECN-A004	AAT	Hanson	
AECN-A005	Argonne/UCI	Brandon Sforzo	bsforzo@anl.gov/mcdonell@ucicl.cu.edu
AECN-A006	Enurga	Sivathanu	Yudaya Sivathanu <sivathan@enurga.com>
AECN-A007	Purdue	Terry Meyer	trmeyer@purdue.edu
AECN-A008	Enurga	Sivathanu	Yudaya Sivathanu <sivathan@enurga.com>
AECN-A009	AFRL	Lightfoot	malissa.lightfoot@us.af.mil
AECN-A010	Argonne	Brandon Sforzo	bsforzo@anl.gov

Ethan Hanson
Design Engineer
Advanced Atomization Technologies
Parker Aerospace & GE Aviation Joint Venture
Gas Turbine Fuel Systems Division
124 Columbia Street
Clyde, NY 14433 USA
direct (315) 902-5285
ethan.hanson@advancedatomization.com

- **Database is starting to grow organically**
  - ***No cost*** **for the injector facilitates participation!**

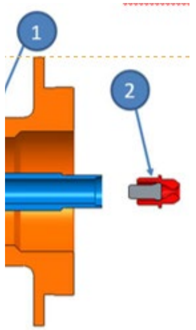
Pressure Swirl Atomizer

- **With Heritage of Legacy RSA, "RSA II" or "AeroECN" now available**
- **Contact Ethan Hanson of AAT**
- **Recent Status of several RSAs (two were with Hunter Mack #5 and #10)**

S/N	Institution	Owner	Comment
AECN-A001	UC Irvine	McDonell	Sealing issues
AECN-A002	AAT	Hanson	
AECN-A003	AAT	Hanson	
AECN-A004	AAT	Hanson	
AECN-A005	UC Irvine	McDonell	Uneven flow, sealing
AECN-A006	UC Irvine	McDonell	Uneven flow, sealing
AECN-A007	Purdue	Terry Meyer	trmeyer@purdue.edu
AECN-A008	UC Irvine	Sivathanu	No flow
AECN-A009	AFRL	Lightfoot	malissa.lightfoot@us.af.mil
AECN-A010	UC Irvine	McDonell	functioning

Ethan Hanson
Design Engineer
Advanced Atomization Technologies
Parker Aerospace & GE Aviation Joint Venture
Gas Turbine Fuel Systems Division
124 Columbia Street
Clyde, NY 14433 USA
direct (315) 902-5285
ethan.hanson@advancedatomization.com

- **Recommendations**
  - ***Return all injectors to AAT for maintenance, flow checks, cleaning***
  - ***Consider adding wrench flats to the injector for tightening onto body***
  - ***Protocol for sealing/tightening (torque, soft washer, etc)***



Spanning the Applications

- Plain jet
- Simplex Atomizer
- Fan Spray*

- Co-axial gas-liquid*
- Plain jet in crossflow?*
- **Airblast**

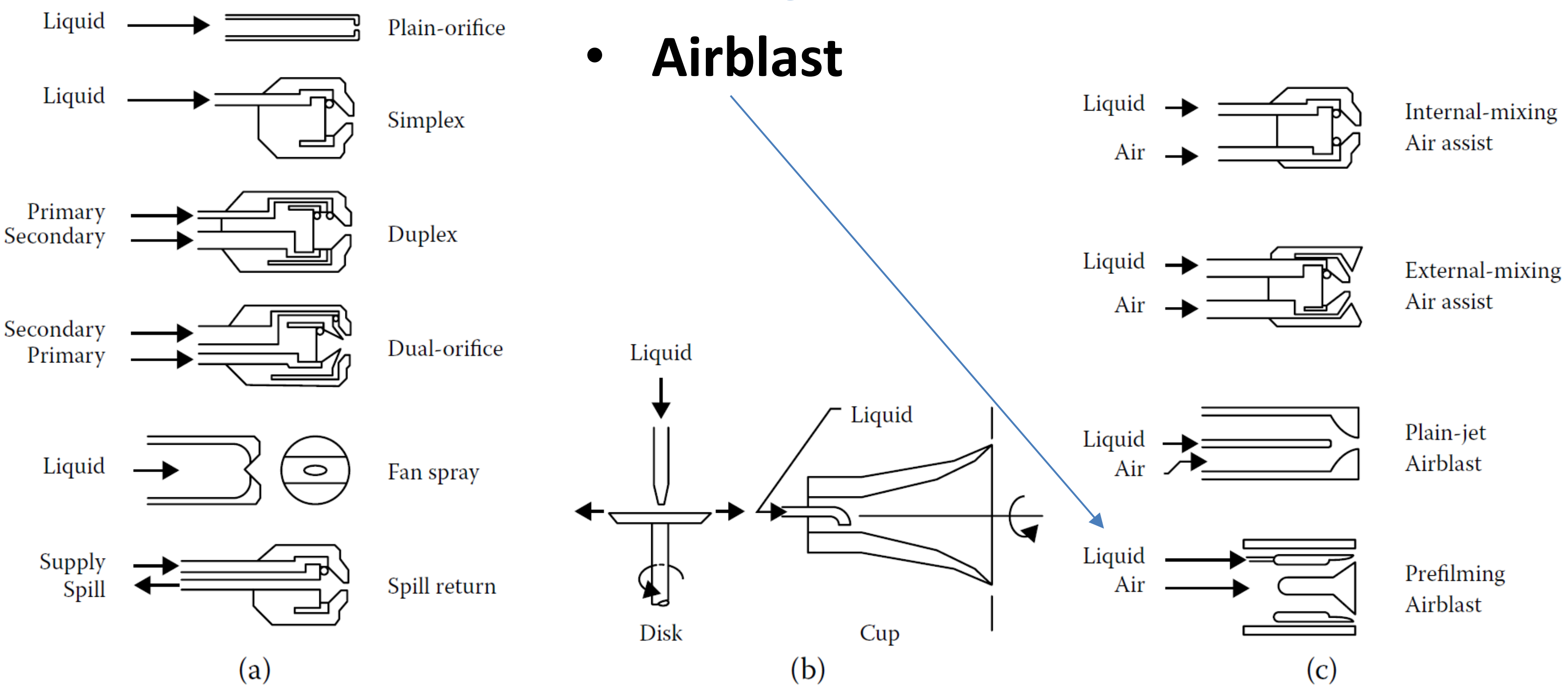
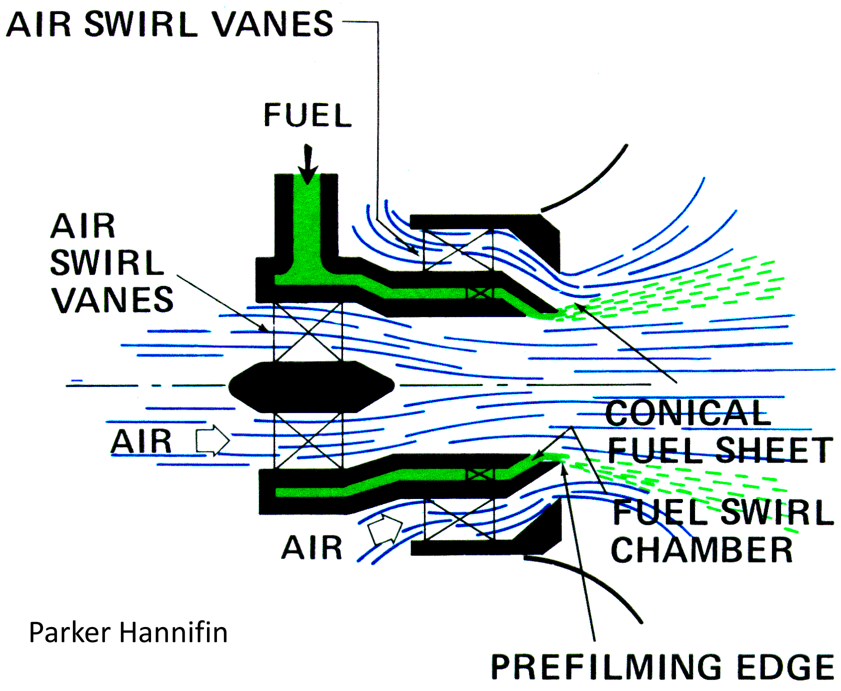


FIGURE 1.2
(a) Pressure atomizers, (b) rotary atomizers, and (c) twin-fluid atomizers.

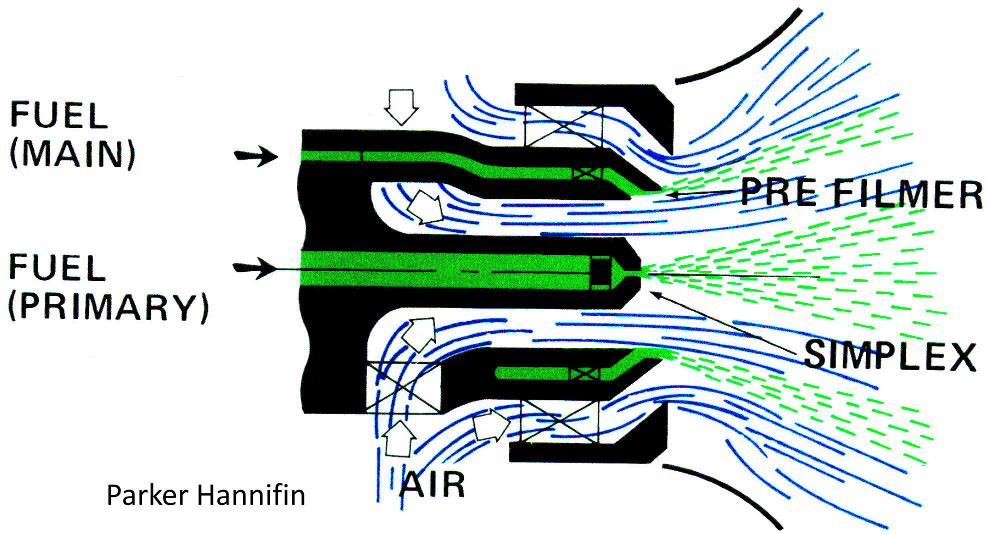
Consider inspiration and leadership for Aerospace and Propulsion TC and AeroECN working group

Gas Turbine Fuel Injectors

- **Ubiquitous in aero applications (Lefebvre, 1960s)**
  - **Solved many issues with mechanical designs, but suffered at startup**
  - **“Hybrid” strategy merged benefits of mechanical (pressure nozzle) with air-blast**



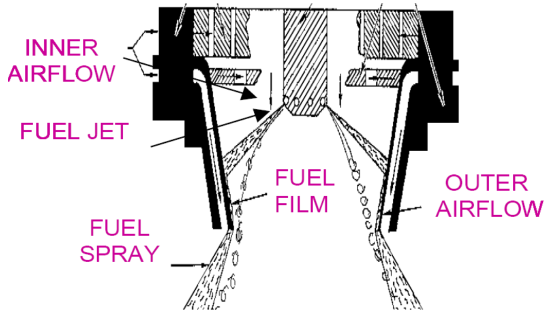
Parker Hannifin



Parker Hannifin

Prefilming

- **Aero-engine industry identified need for concept with features/conditions *relevant* to that industry**
  - **Insights from measurements**
  - **Validation data for SOA simulation methods**
  - **"Aero Spray working group" established some guidelines of interest specific to this industry**



McKinney et al., 2007
Pratt & Whitney High Shear Injector

Jet in Crossflow????

Foust, et al. 2012
TAPS

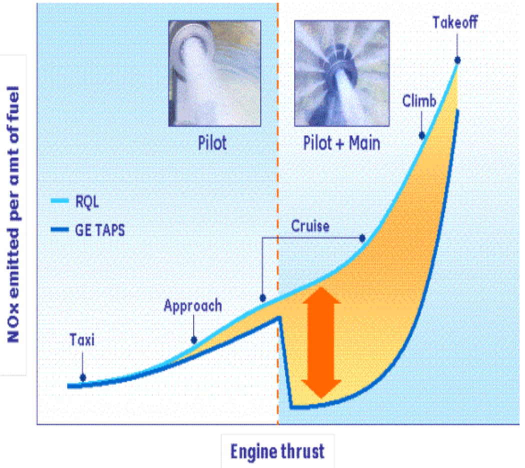


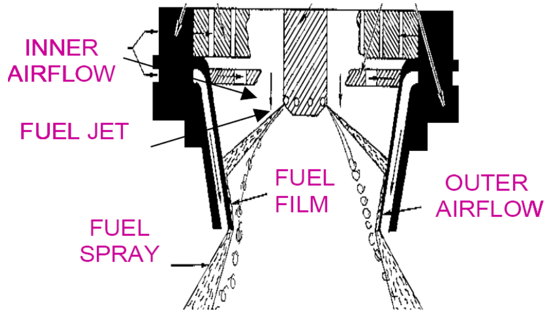
Table 1. Priorities of aero-spray working group for objective of testing with consensus responses.

Question	Concensus
What key fluid physics must be included in the atomizer/injector design?	1. pressure swirl, 2. prefilming/surface filming, 3. jet in crossflow
If high pressure and temperature operating targets are not achievable, what parameter(s) are the most important to match relative to the target conditions?	Momentum ratio, We, Oh, T3/P3 above fuel critic… Some unknowns exist
Following high pressure, low temperatures testing, which conditions should be next target?	High P3, HighT3
What parametric variations are desired for Phase I testing?	fuel, air pressure drops (flow rates), all atomiza… modes
…litional diagnostics are desired for boundary …	1. Inlet boundaries: flow rate and velocities enter… each of the nozzle passages.2. Within the injector test section: x-ray measurements of the fuel lig… and droplets, PIV as well as PDPA
… testing …	…itical, though desired, characterize … cannot measure the … we nee…

Sforzo, B., Kimber, A., Model, J. (2024). Development of an Aerospray Characterization Program and Design of a Non-Proprietary Gas Turbine Engine Atomizer, Paper AIAA-2024-0583, SciTech, Jan.

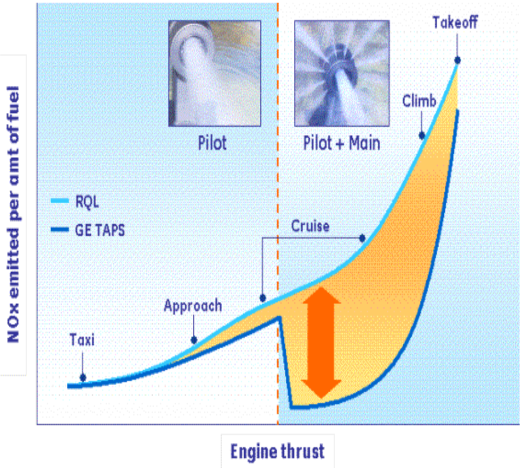
Prefilming

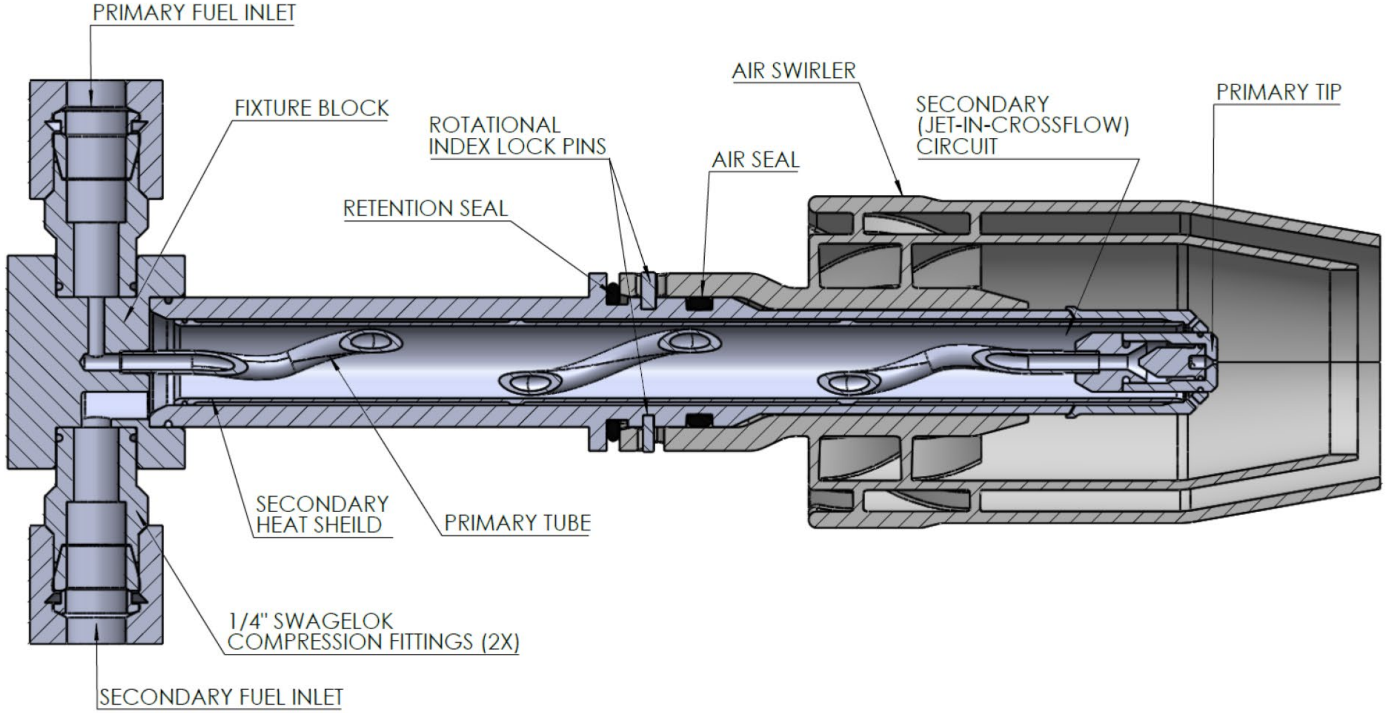
- **Configuration 1**
  - **Captures the "jet in crossflow" impingement strategy utilized in advanced designs from 10+ years ago**



McKinney et al., 2007
Pratt & Whitney High Shear Injector

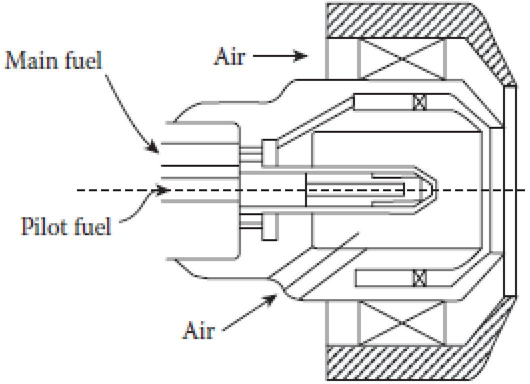
Foust, et al. 2012
TAPS





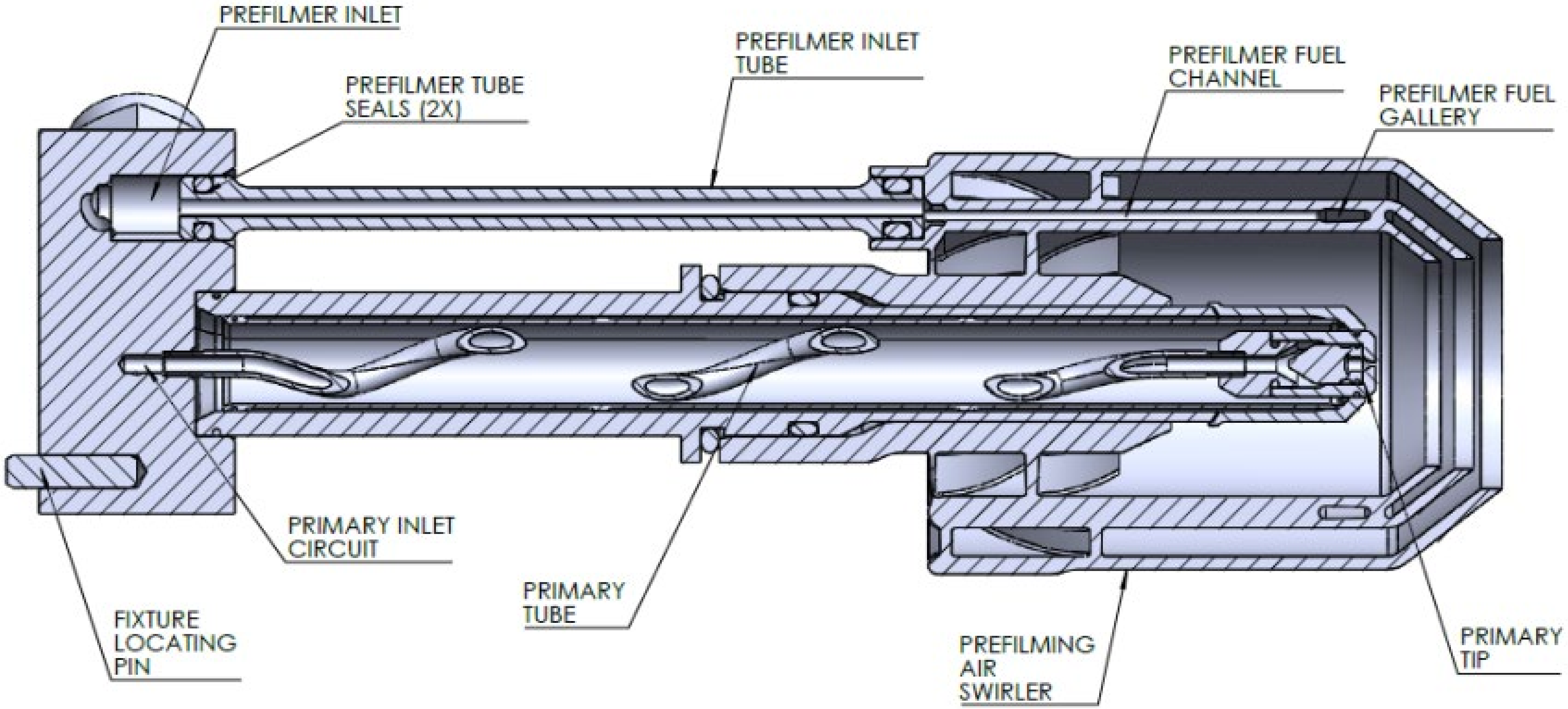
Sforzo, B., Kimber, A., Model, J. (2024). Development of an Aerospray Characterization Program and Design of a Non-Proprietary Gas Turbine Engine Atomizer, Paper AIAA-2024-0583, SciTech, Jan.

Prefilming



Rizk, et al. (1996). AIAA Paper 96-2628

- **Configuration 2—Hybrid Concept**
  - **Simplex Tip for start up**
  - **"Fuel Gallery" type filmer**



Sforzo, B., Kimber, A., Moder, J. (2024). Development of an Aerospray Characterization Program and Design of a Non-Proprietary Gas Turbine Engine Atomizer, Paper AIAA-2024-0583, SciTech, Jan.

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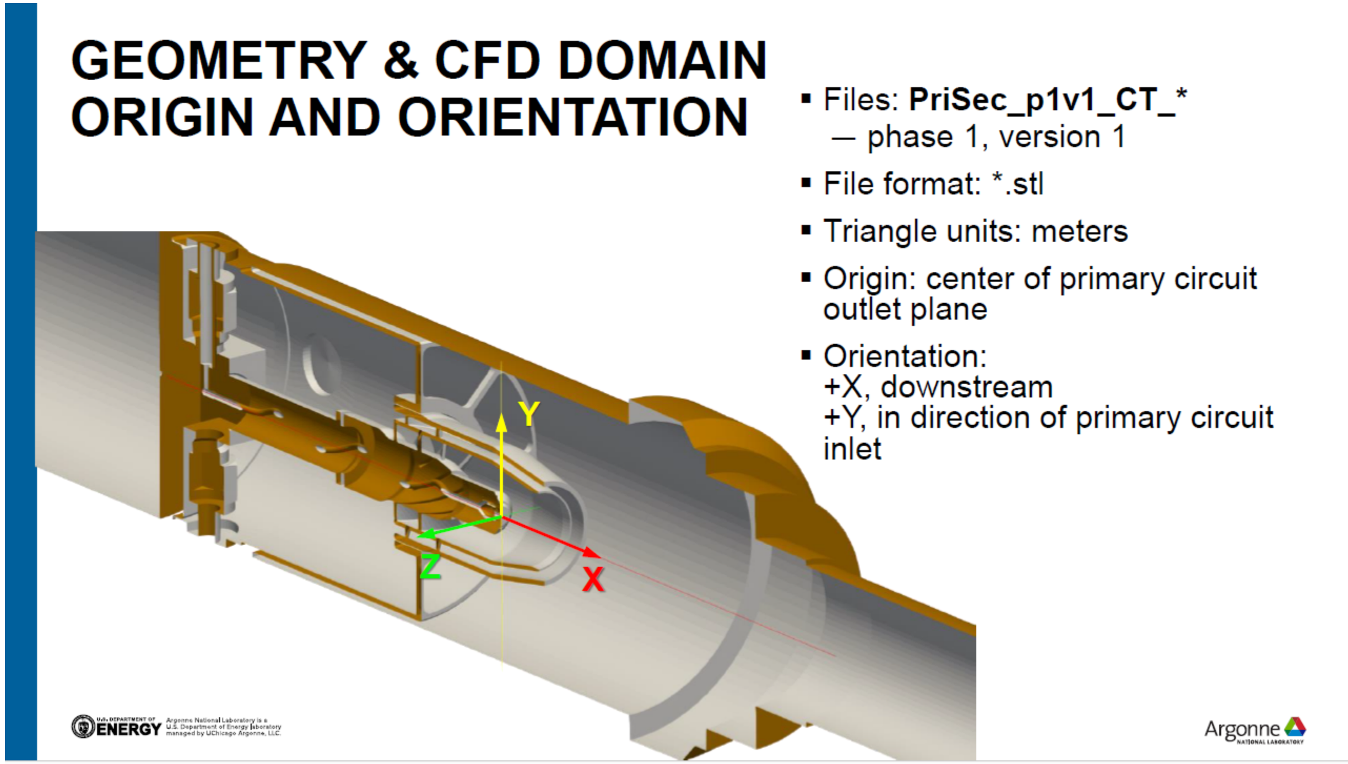
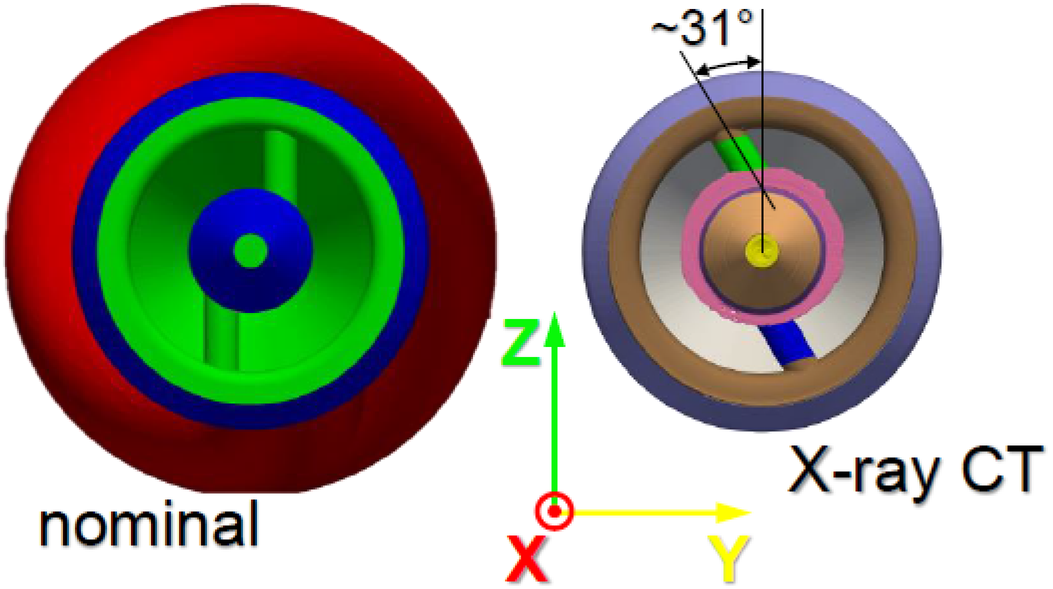
(630) 252-9175

Prefilming

- **Internal Geometry**
  - **As designed and CT informed both recently available/1**



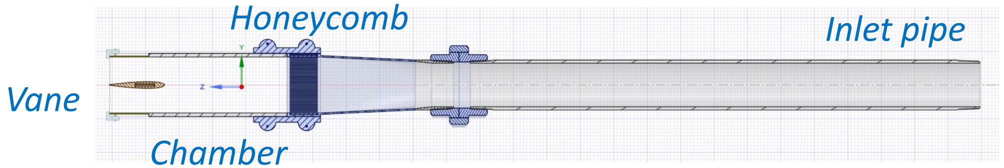


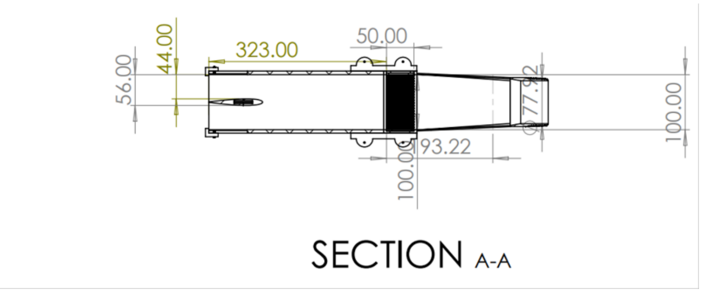
- Assembly of primary circuit internal components not indexed: internal feed passages **clocked** differently from nominal

/1 Brandon Sforzo, Argonne Nat'l Lab 630 252 9175 bsforzo@anl.gov

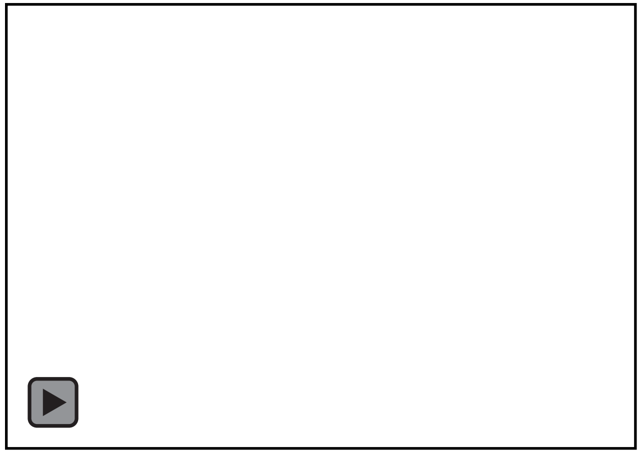
Prefilming

- **2D air-blast concept has been independently developed by a few groups and could offer another "canonical design"**





UC Irvine/MHI



Gepperth, Karlsruhe Inst. Tech

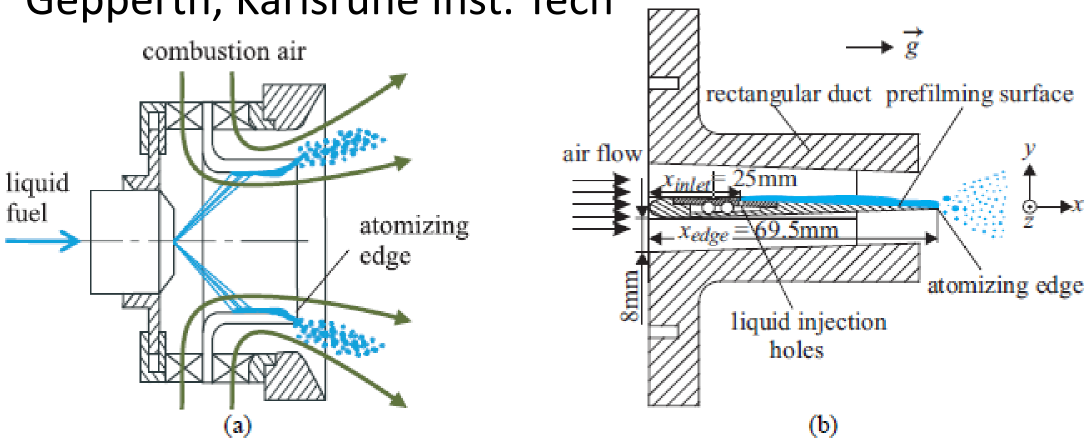
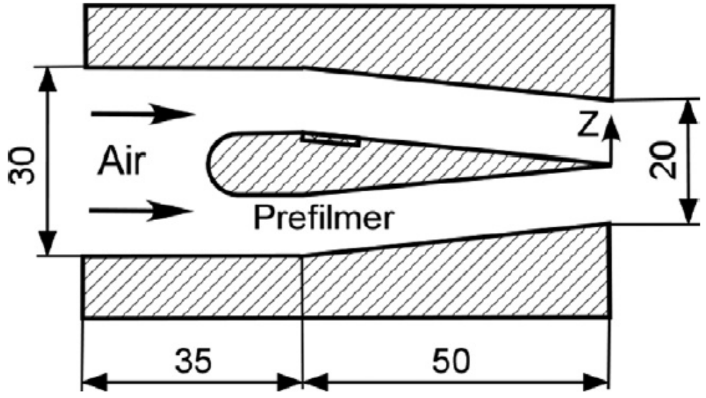


Figure 1. (a) typical gas turbine pre-film atomizer, (b) experimental atomizer

Inamura, Hirosaki University



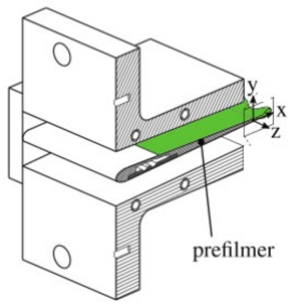
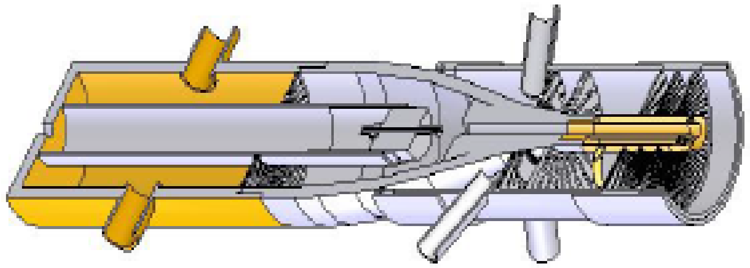


Fig. 2. Test atomizer (unit: mm).

Other Perspectives

- **Turbulent Combustion of Sprays workshops (ERCOFTAC*)**
  - **7 workshops thus far (SIG 12) on Best Practice Guidance on CFD for Dispersed Multiphase Flow**
  - **Focus has been more on identifying a specific data set (usually existing, but perhaps recent) and distributing to simulation teams**
    - ✓ **Generally the focus of the workshops is on *comparing results with the target data* set but also asking specific questions regarding how certain parameters influence the simulations**
    - ✓ **<u>Not a "portable device" which is the focus of the current overview</u>**



Gounder, Kourmatzis, and Masri (2012). Turbulent Piloted Dilute Spray Flames: Flow Fields and Droplet Dynamics, *Comb Flame*, Vol 159, 3372-3397
Masri and Gounder (2010). Turbulent Spray Flames of Acetone and Ethanol Approaching Extinction, *Comb Sci Tech* 182, 702-715

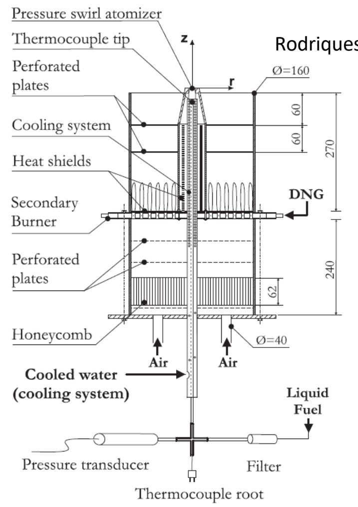


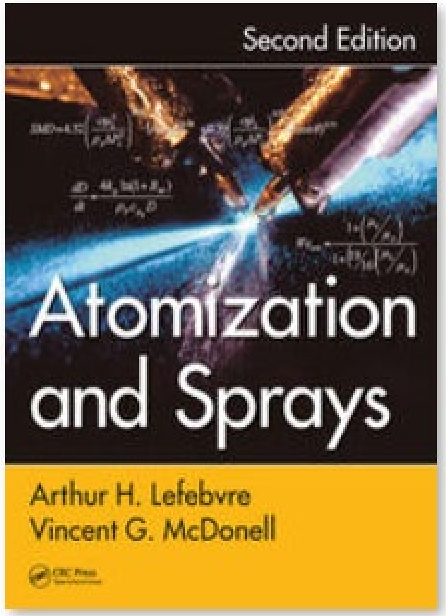
Fig. 1. Schematic of the burner facility with relevant dimensions in millimeters.

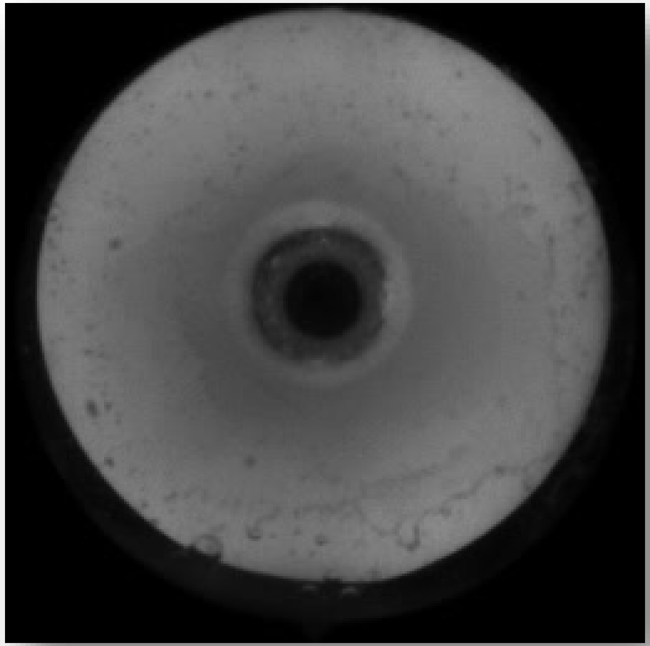
Rodriques, Tummers, van Veen, and Roekaerts (2015). C&F, Vol 162

***European Research Community on Flow, Turbulence, and Combustion**

Concluding Remarks

- **Opportunity for the community to collaborate**
- **ILASS-Americas will have a session discussing results from recent RSA studies….**
  - **Bozeman, Montana 18-21 May 2025**
- **Try it yourself…..**
  - **UCI Atomization & Sprays Course**
    - ✓ **14-15 March 2025**
    - ✓ **Hands on measurements**
    - ✓ **UCICL.uci.edu**
    - ✓ **Also gas turbine combustion course**





Kufferath, et al. (2025). ILASS Americas

Thank you!

Perspectives on “Reference Sprays” for aligning the spray community

ILASS-Americas Webinar
Aerospace Propulsion and Power Technical Committee
Virtual
27 February 2025

Vincent McDonell
mcdonell@UCICL.uci.edu

UCI Combustion Laboratory
UCIrvine | University of California

Other Perspectives

- **Turbulent Combustion of Sprays workshops (ERCOFTAC*)**
  - **7 workshops thus far**
  - **Focus has been more on identifying a specific data set (usually existing, but perhaps recent) and distributing to simulation teams**
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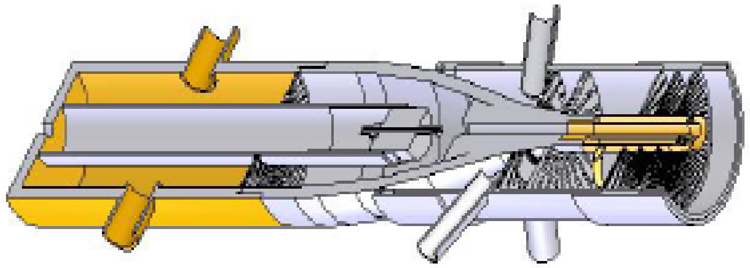

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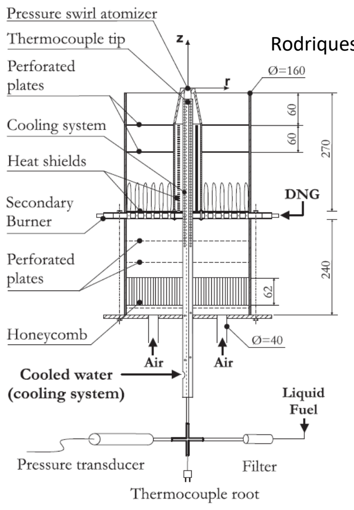


Fig. 1. Schematic of the burner facility with relevant dimensions in millimeters.

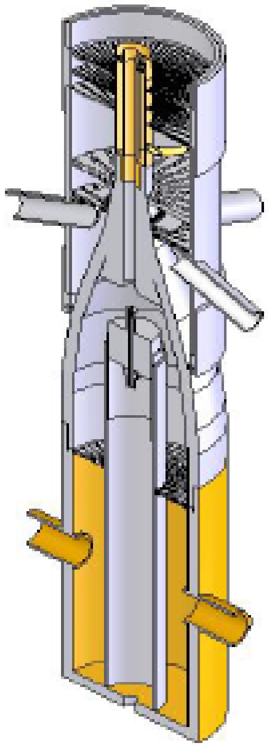
Rodriques, Tummers, van Veen, and Roekaerts (2015). C&F, Vol 162

***European Research Community on Flow, Turbulence, and Combustion**

Other Perspectives

- **Turbulent Combustion of Sprays workshops (ERCOFTAC)**
  - **7 workshops thus far**
  - **Target spray (flame) experiments identified as challenge datasets**

  - **TCS 1-4—2009-2015**
    - ✓ **Prof Masri—Sydney Databases**
    - ✓ **Piloted Spray Burner**



Non-Reacting, Non-Evaporating
Non-Reacting, Evaporating (Ethanol)
Reacting (Ethanol)
Reacting (Acetone)

Gounder, Kourmatzis, and Masri (2012). Turbulent Piloted Dilute Spray Flames: Flow Fields and Droplet Dynamics, *Comb Flame*, Vol 159, 3372-3397
Masri and Gounder (2010). Turbulent Spray Flames of Acetone and Ethanol Approaching Extinction, *Comb Sci Tech* 182, 702-715

Other Perspectives

- **Turbulent Combustion of Sprays workshops (ERCOFTAC)**
  - **7 workshops thus far**
  - **Target spray (flame) experiments identified as challenge datasets**
  - **TCS 5--2015**
    - ✓ **Adds Delft Spray in Vitiated Coflow**

Rodriques, Tummers, van Veen, and Roekaerts (2015). C&F, Vol 162

Table 2
Summary of measurements locations for A_{II} and H_{II} test cases.

Measurement technique	z (mm)	Comment
LDA	0, 20, 25, 30, 35, 40, 45, 50	Coflow radial profiles, spray center axis
CARS	0, 15, 20, 30, 40, 45, 50, 60	Coflow radial profiles, spray region
Flue gas analyser	0	Coflow radial profiles
PDA	8, 10, 12, 15, 20, 30, 35, 40, 45	Spray region, steps of 1 mm

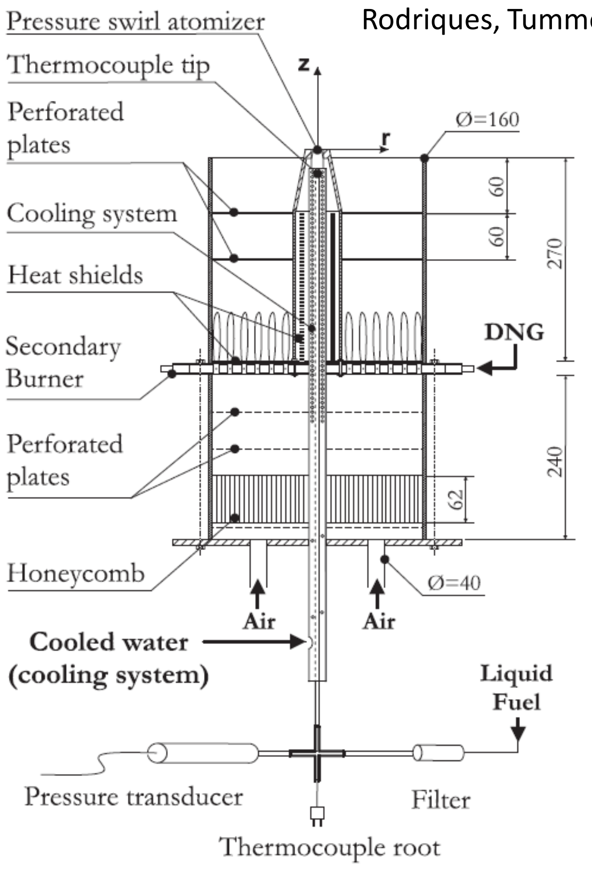


Fig. 1. Schematic of the burner facility with relevant dimensions in millimeters.

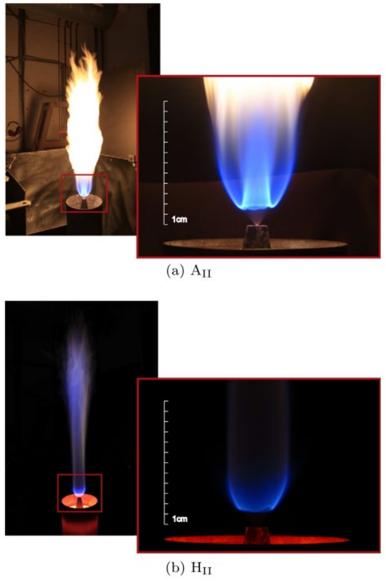
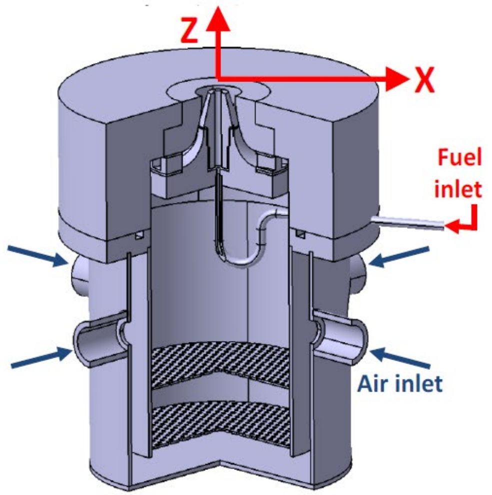


Fig. 2. Images of test cases with 0.8 s exposure time and identical aperture. The field-of-view of the inset has dimensions 220 × 170 mm² (width × height).

Other Perspectives

- **Turbulent Combustion of Sprays workshops (ERCOFTAC)**
  - **7 workshops thus far**
  - **Target spray (flame) experiments identified as challenge datasets**

  - **TCS 6--2017**
    - ✓ **Adds CORIA Rouen Spray Burner (Renou)**



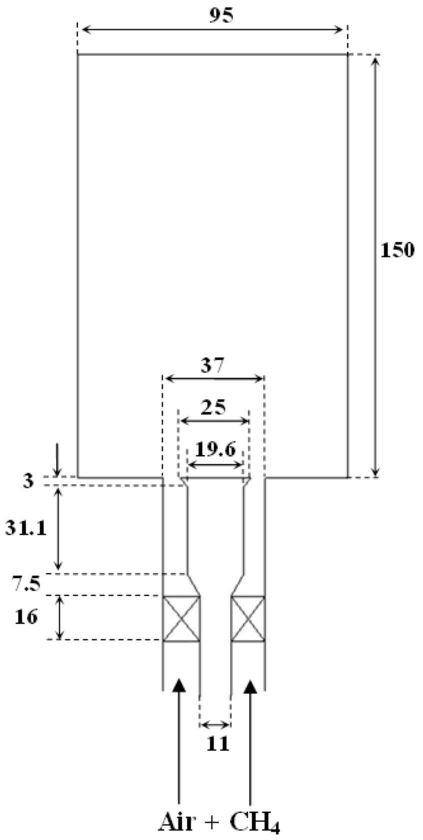
Type of data (raw and post-processed)	Technique	Conditions	Mesh	Publication
Fuel droplet / ligaments and conical sheet images - Height of atomization - Droplet sphericity	Microscopic shadowgraphy	NRC	7*5 mm and 2.4*1.8 mm	Not published
Air velocity - X and Z components - 40 000 samples or 30 s acquisition time	PDA	RC/NRC	Z mini = 5 mm Z maxi = 50 mm	Partially published in [2]
Air velocity - *Velocity fields (instantaneous, mean and rms fluctuations)* - *Axial and radial velocities* - *From velocity fields a range of spatial derivatives is calculated such as vorticity, shear tress, turbulent kinetic energy*	HS-PIV	RC/NRC	Figure 2	Not published
Fuel droplet velocity - X and Z component - 40 000 samples or 30 s acquisition time - Conditional average with the droplet diameter.	PDA	RC/NRC	Z mini = 5 mm Z maxi = 50 mm	Partially published in [2]
Fuel droplet distribution size (histograms)	PDA	RC/NRC	Z mini = 5	Partially
Flame shape - OH instantaneous field - Lift height (averaged and Rms) - Radial location of lift (averaged and Rms)	OH-PLIF	RC	Figure 2	Partially published in [2, 3]
Fuel droplet temperature - Temporal average over 400 recordings - Spatial average for all the droplets contained within the measurement volume	C-GRT	RC/NRC	Z mini = 20 mm Z maxi = 70 mm	Partially published in [3]
Fuel droplet temperature - Instantaneous measurement (few ns) - Spatial average for all the droplets contained within the measurement volume (0.92 mm^3) - Data coupled with OH-PLIF measurements in order to provide temperature data conditioned to the flame front location	I-GRT	RC	Radial profile at Z=35 mm	Published in [3]
Dynamics of flame shape - Temporal evolution of 2D OH fields (10 kHz) - Extinction phenomena - Re-ignition phenomena	HS-OH-PLIF	RC	Figure 2	Not published
Ignition probability map - Laser ignition - Constant energy - Statistics over 30 trials - Visualization of the kernel flame development until flame stabilization	Laser induced spark ignition	NRC	Z mini = 5 mm Z maxi = 45 mm	Not published
Turbulence / flame interactions - Flame position coupled to the corresponding velocity field	HS-PIV	RC	Figure 2	Not published
Droplet / flame interactions - Qualitative fuel droplet-reaction zone interactions	HS-OH-PLIF	RC	Figure 2	Not published

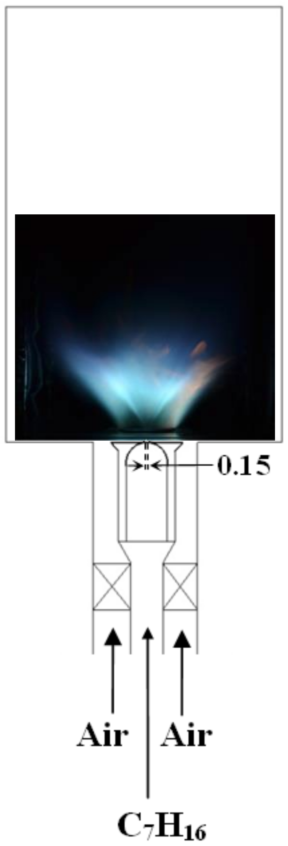
1 Cordier, Vandel, Cabot, Renou, and Boukhalfa (2013). Comb Sci Tech, Vol 185, 379-407
2 Shum-Kivan, et al (2016). Proceedings of Comb Inst.
3 Verdier, et al., (2016). Proceedings of Comb Inst.

Other Perspectives

- **Turbulent Combustion of Sprays workshops (ERCOFTAC)**
  - **7 workshops thus far**
  - **Target spray (flame) experiments identified as challenge datasets**
  - **TCS 6--2017**
    - ✓ **Adds Cambridge Swirl Burner (Mastorakos)**

FUEL	Mie scattering from spray	OH* (Abel)	OH-PLIF (mean & 10kHz)	CH2O-PLIF (simultan. with OH-PLIF)	PDA (SMD, size distribution , Velocity)	Dynamics of blow-off	Refs	Comments
Cold flow (no fuel)	-	-	-	-	Air flow axial and swirl	-	[1, 2]	Used for grid independence etc
Ethanol	X	X	X	-	X	X	[3,4,5]	CFD at Cambridge completed
Heptane	X	X	X	X	X	X	[3,6]	Plan to simulate at Cambridge
Decane	X	X	X	-	X	X	[3]	
Dodecane	X	X	X	-	X	X	[3]	Currently simulated at Cambridge
Kerosene (A1)	To do	X	X	"Fuel PLIF"	To do	To do	Unpubl. A ppt is available [7]	These kerosenes are standard, part of the USA National Jet Fuel Combustion Programme
Kerosene (C1)	To do	X	X	"Fuel PLIF"	To do	To do	Unpubl. A ppt is available [7]	
Kerosene (C5)								To do



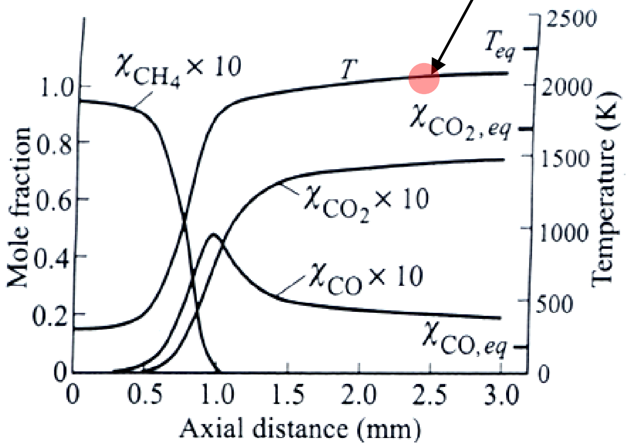


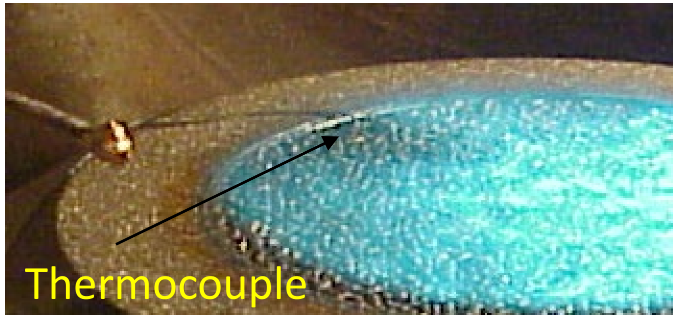
1. A. Cavaliere PhD thesis, U of Cambridge. For the physics, but with different atomiser, also see: Cavaliere, D.E., Kariuki, J. & Mastorakos, E. (2013) A comparison of the blow-off behaviour of swirl-stabilised premixed, non-premixed and spray flames. *Flow, Turbulence and Combustion* **91**, 347-372. doi: 10.1007/s10494-013-9470-z
2. Tyliszczak, A., D.E. Cavaliere & Mastorakos, E. (2014) LES/CMC of blow-off in a liquid fuelled swirl burner. *Flow, Turbulence and Combustion* **92**, 237-267. doi: 10.1007/s10494-013-9477-5
3. R. Yuan PhD thesis, U of Cambridge. Draft paper upon request.
4. Giusti, A. & Mastorakos, E. (2016) Detailed chemistry LES/CMC simulation of a swirling ethanol spray flame approaching blow-off. To appear in *Proceedings of the Combustion Institute.* doi: 10.1016/j.proci.2016.06.035
5. Giusti, A., Kotzagianni, M. & Mastorakos, E. (2016) LES/CMC simulations of swirl-stabilised ethanol spray flames approaching blow-off. To appear in *Flow, Turbulence and Combustion.*
6. Yuan, R., Kariuki, J., Dowlut, A., Balachandran, R. & Mastorakos, E. (2015) Reaction zone visualisation in swirling spray n-heptane flames. *Proceedings of the Combustion Institute* **35**, 1649-1656. doi: 10.1016/j.proci.2014.06.012
7. Dr. Jenni Sidey, presentation to NJFCP, June 2016. Please contact Dr. Sidey at jams4@cam.ac.uk

Inspiration: Analogous Combustion Reference Flame

- **e.g., Temperature Calibration**
  - **Methane-Air Φ = 1, 2.5 mm**

T_{calc}, T_{meas}, T_{CARS}



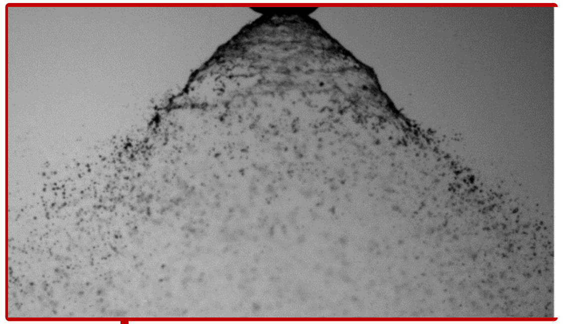
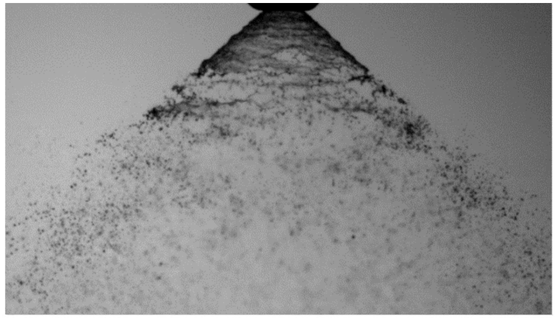
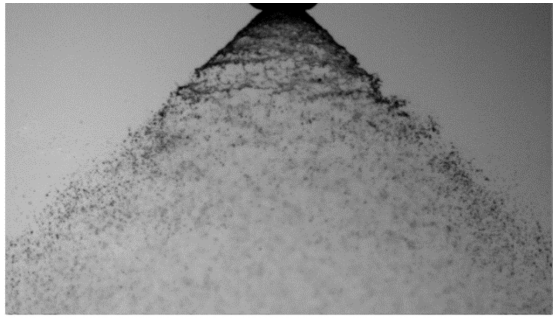


			CH4 Rotometer	Air Rotometer			
Num	CH4	Air	Setting	Setting	Phi	T, adibatic	T, CARS
()	(slpm)	(slpm)	(mm)	(mm)	()	K	K
1	1.10	15.00	48	62	0.70	1838	1706
2	1.31	15.60	57	65	0.80	1997	1765
3	1.31	12.40	57	51	1.00	2226	1790
4	1.31	11.31	57	47	1.10	2211	1754
5	1.31	10.40	57	43	1.20	2137	1723
6	1.42	15.00	62	62	0.90	2134	1799
7	1.73	20.63	76	86	0.80	1997	1828
8	1.73	16.50	76	68	1.00	2226	1886
9	1.73	14.96	76	62	1.10	2211	1826
10	1.74	15.00	76	62	1.10	2211	1818
11	1.73	13.70	76	57	1.20	2137	1828
12	1.73	11.80	76	49	1.40	1980	1813
13	2.05	15.00	90	62	1.30	2057	1878
14	2.29	15.00	100	62	1.45	1942	1915
15	2.55	30.30	112	126	0.80	1997	1967
16	2.55	27.00	112	112	0.90	2134	1976
17	2.55	24.14	112	100	1.00	2226	2009
18	2.55	22.00	112	91	1.10	2211	1934
19	2.55	20.20	112	84	1.20	2137	1883
20	2.55	17.43	112	72	1.39	1980	1929
21	3.42	36.18	150	150	0.90	2134	2110
22	3.42	32.40	150	134	1.00	2226	2100

2226 vs 1790 K

Data Set--High-Speed Video

METHANOL

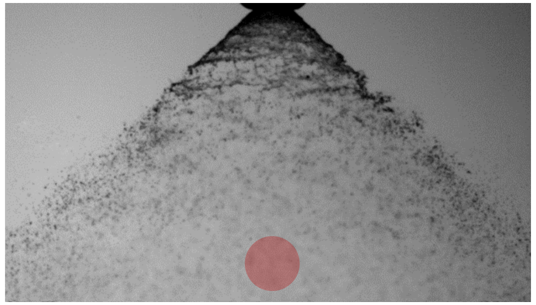
	25 psi		50 psi		100 psi
FN:	2.06	FN:	2.01	FN:	1.95
FN:	2.04	FN:	2.00	FN:	1.95
Angle:	110.0°	Angle:	94.4°	Angle:	90.8°

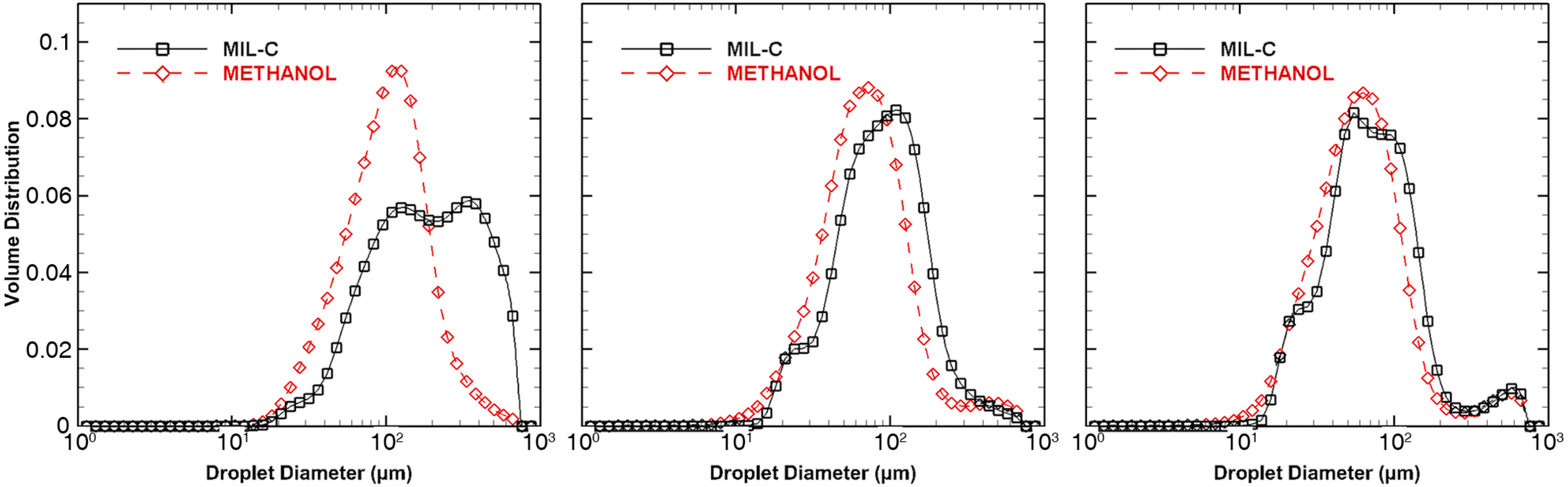
Negligible change in FN and spray angle between MIL-C and methanol in full atomization mode.

Leask, S.B., Li, A.K., McDonell, V., and Samuelsen, G.S. (2018). Evaluation of Research Simplex Atomizers and a Measurement Standard, ICLASS 2018, Chicago, July
Leask, S.B., Li, A.K., McDonell, V., and Samuelsen, G.S. (2019). Preliminary Development of a Measurement Reference Using a Research Simplex Atomizer, ASME Journal of Fluids Engineering, Vol 141

Data Set--Liquid Type Comparison

- Laser Diffraction of MIL-C and Methanol
  - Taken 2 inches downstream of the centerline
  - 25 psi, 50 psi, and 100 psi
  - Different liquids





25 psi 50 psi 100 psi

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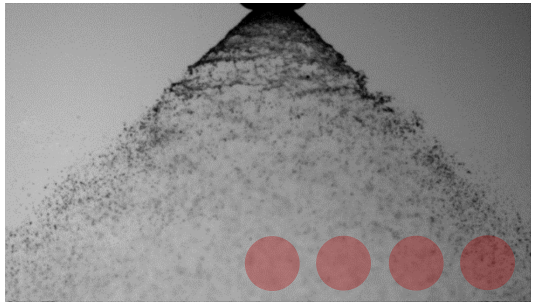
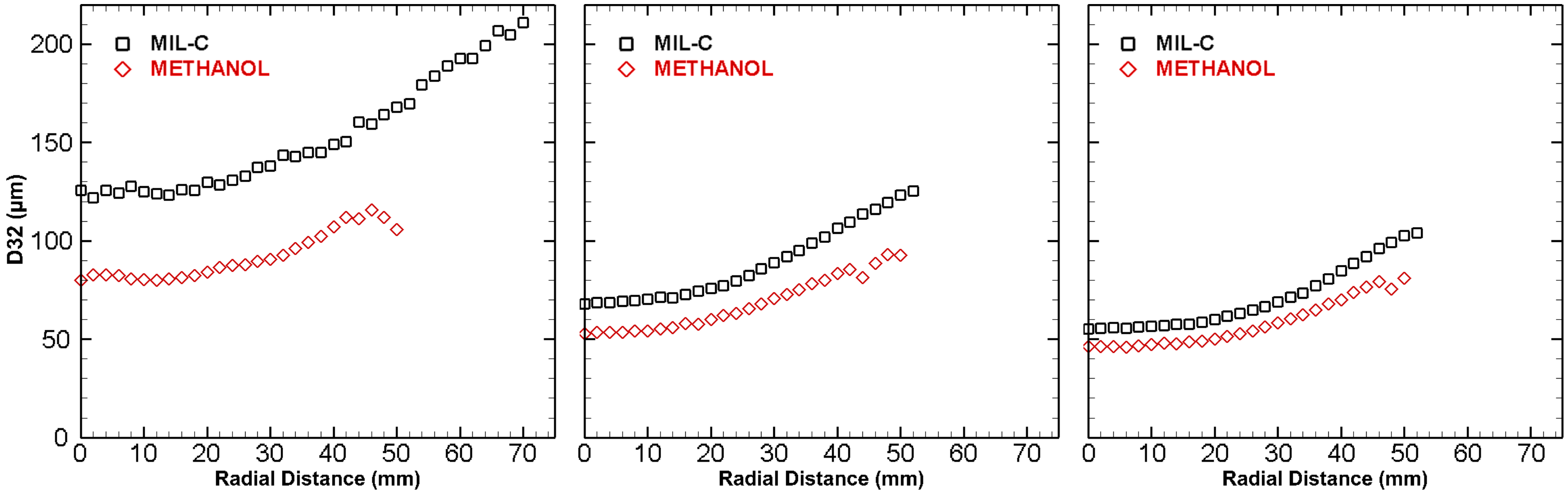
Leask, S.B., Li, A.K., McDonell, V., and Samuelsen, G.S. (2019). Preliminary Development of a Measurement Reference Using a Research Simplex Atomizer, ASME Journal of Fluids Engineering, Vol 141

Data Set--Liquid Type Comparison

- Radial SMD Measurements
  - Line-of-sight measurements
  - MIL-C and methanol
  - Improved agreement as pressure increases
  - SMD generally between 50 to 100 microns





25 psi 50 psi 100 psi

Leask, S.B., Li, A.K., McDonell, V., and Samuelsen, G.S. (2018). Evaluation of Research Simplex Atomizers and a Measurement Standard, ICLASS 2018, Chicago, July

Leask, S.B., Li, A.K., McDonell, V., and Samuelsen, G.S. (2019). Preliminary Development of a Measurement Reference Using a Research Simplex Atomizer, ASME Journal of Fluids Engineering, Vol 141

Outline

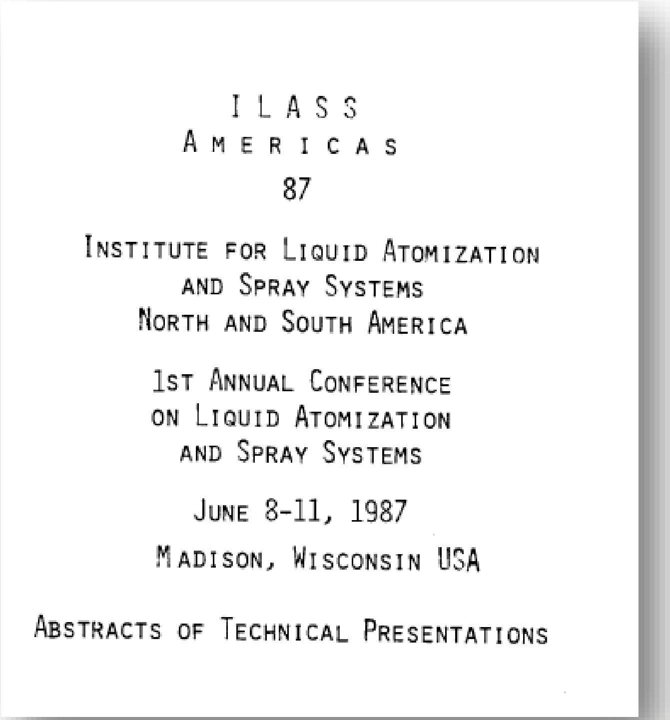
- Motivation
- Historical Perspective
- Current Developments
- Outlook

Concluding Remarks

- **A pressure swirl reference spray ("AeroECN") has been presented/discussed**

- **Potential to *align spray researchers* to build significant databases using *experiments* and *simulations***
  - ***Please join the fun!***

- **ILASS-Americas (www.ilass.org) will have a session on collaborative results from "AeroECN"**
  - **17 – 20 May 2020, Madison Wisconsin (birthplace of ILASS-Americas in 1987 due to collaboration of Hiroyasu, Tanasawa, Kurabayashi, Crosby, Eisenklam (Europe), Simmons, and Chigier)**


ILASS
AMERICAS
87

INSTITUTE FOR LIQUID ATOMIZATION
AND SPRAY SYSTEMS
NORTH AND SOUTH AMERICA

1ST ANNUAL CONFERENCE
ON LIQUID ATOMIZATION
AND SPRAY SYSTEMS

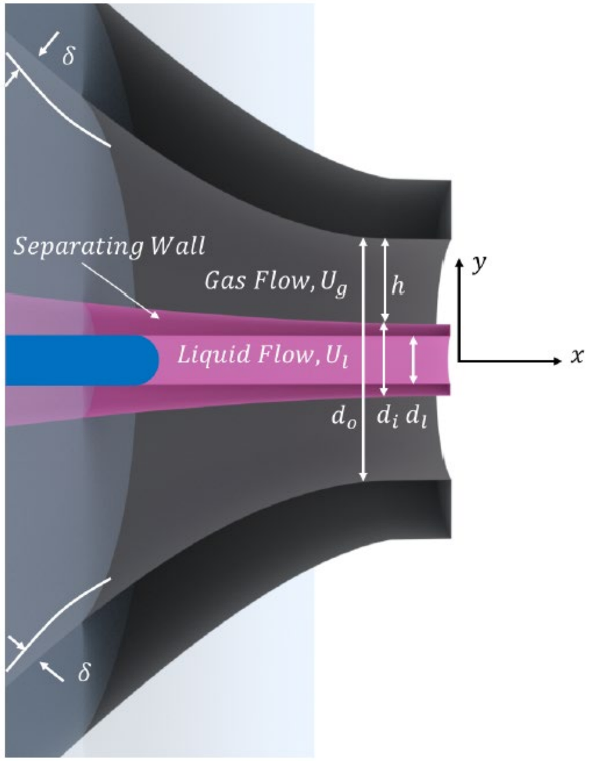
JUNE 8-11, 1987

MADISON, WISCONSIN USA

ABSTRACTS OF TECHNICAL PRESENTATIONS

Co-Axial Jet

- **MURI Injector**

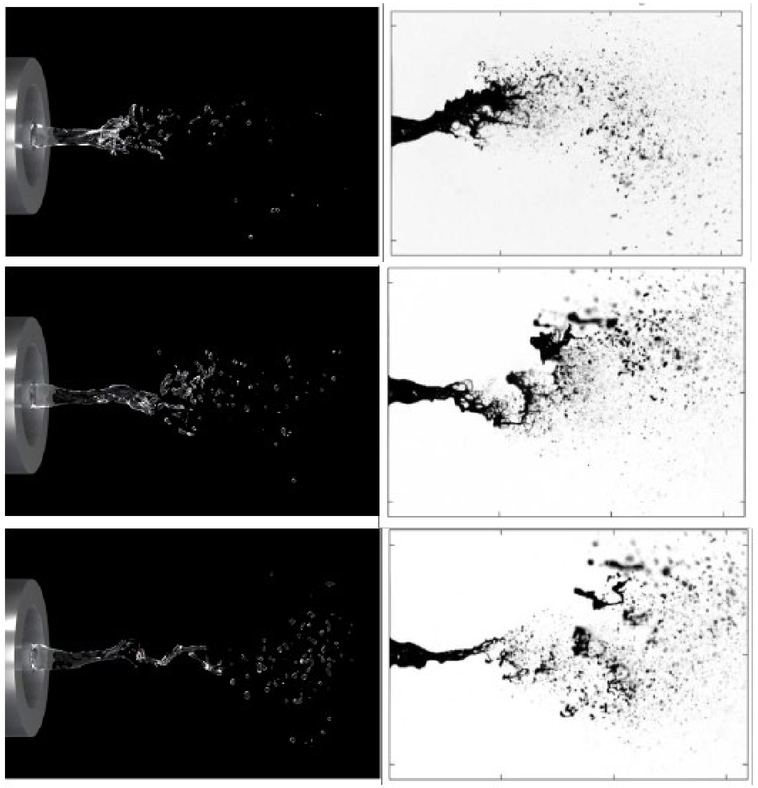


Case 1 / Case 2

Re_{gas} = 15,000 / 37,500 **q** = 5 / 27.8

Re_{liq} = 1000

We_{Δ} = 4.54 / 20.5 Δ = 100 micron



(b) Case 2

Machicoane and Aliseda (2017). Experimental Characterization of a Canonical Coaxial Gas-Liquid Injector, ILASS-Americas 29th Annual Conference, Georgia Tech, May
Wu, Chiodi, and Desjardins (2018). Effect of Momentum Ratio on the Primary Breakup Dynamics of a Canonical Coaxial Atomizer with Comparison to X-Ray Radiography, ICLASS 2018, Chicago, IL, July

Spanning the Applications

- Plain jet
- Simplex Atomizer
- Fan Spray

- **Co-axial gas-liquid**
- Plain jet in crossflow?
- Airblast

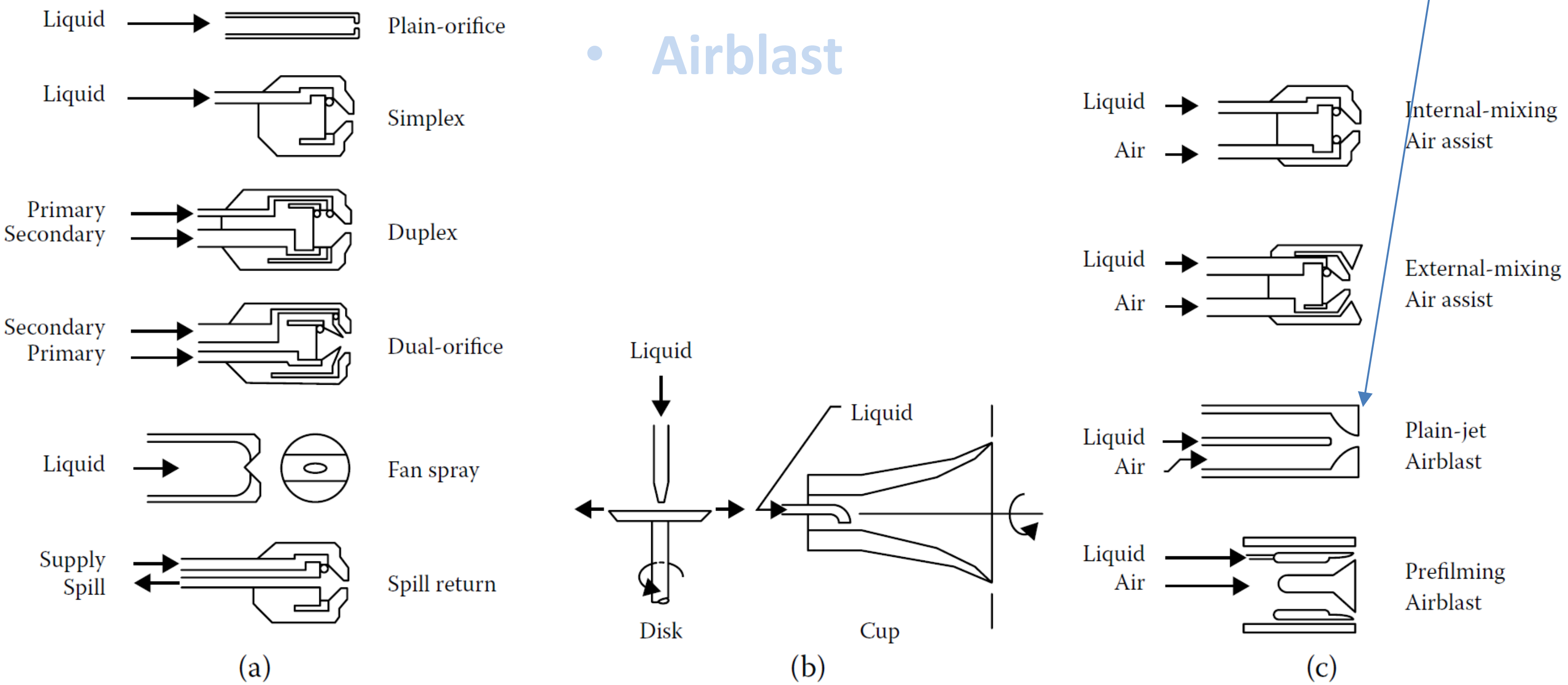
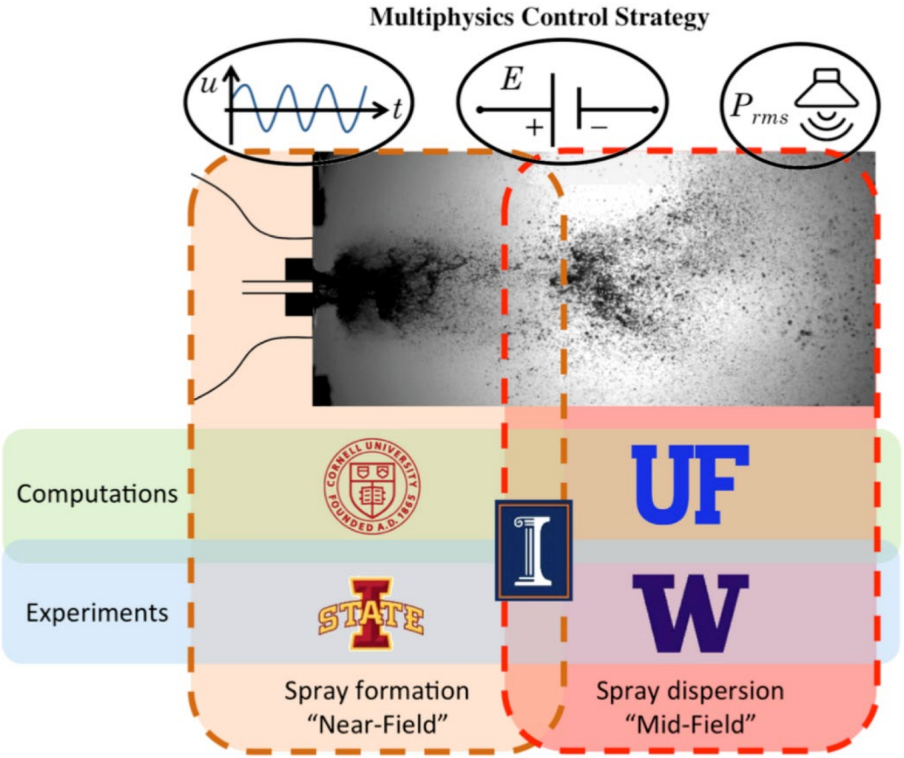


FIGURE 1.2
(a) Pressure atomizers, (b) rotary atomizers, and (c) twin-fluid atomizers.

Co-Axial Jet

- **MURI Injector**

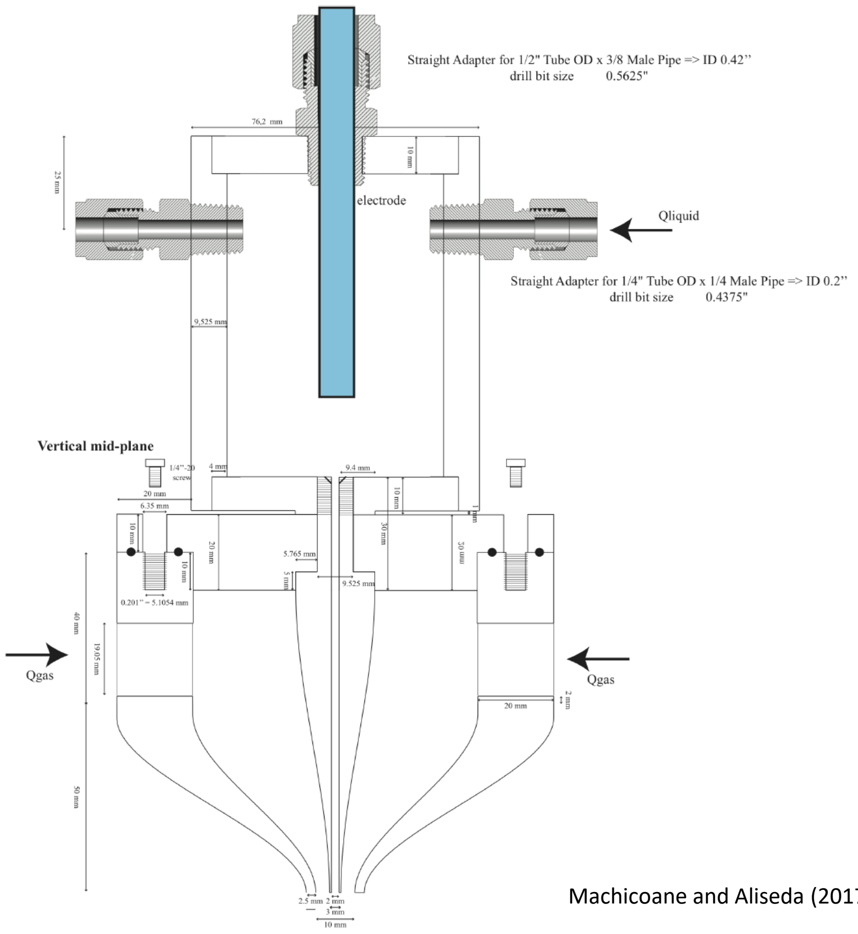


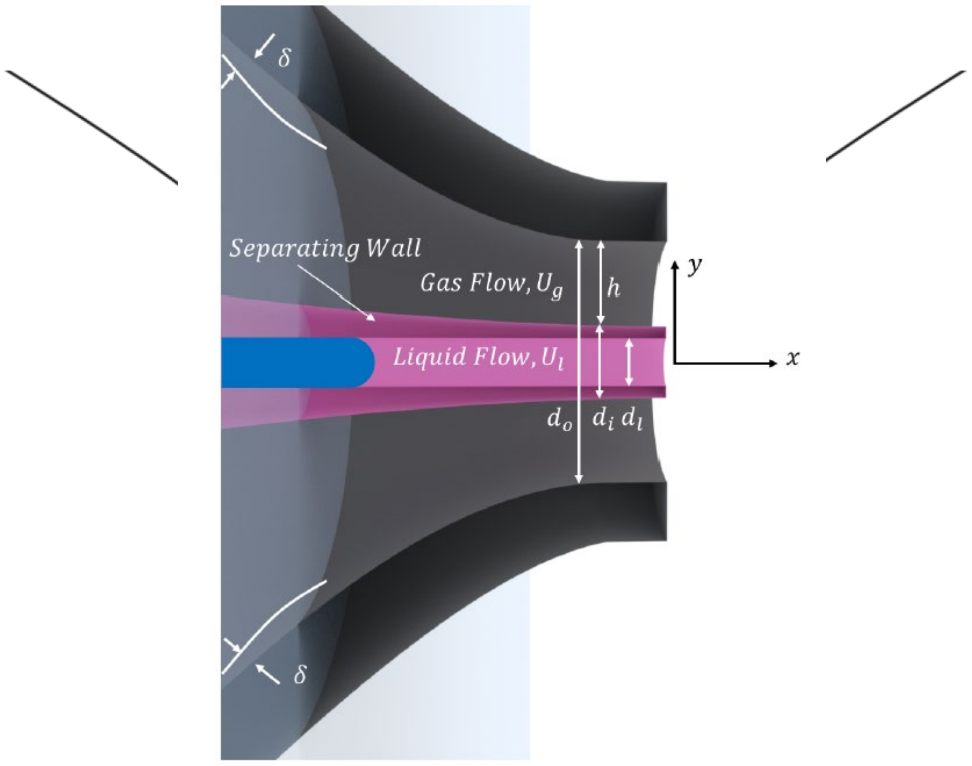
http://blogs.cornell.edu/spraycontrolmuri

Co-Axial Jet

- **MURI Injector**

Re,gas = 10,000 – 25,000
Re,liq = 1000
We,gas = 10-10,000

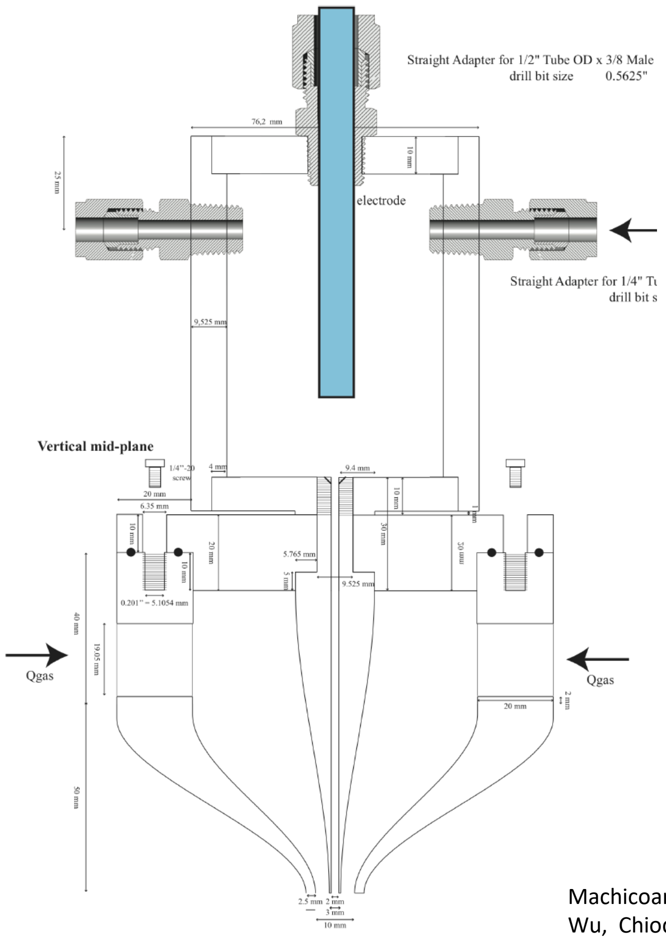


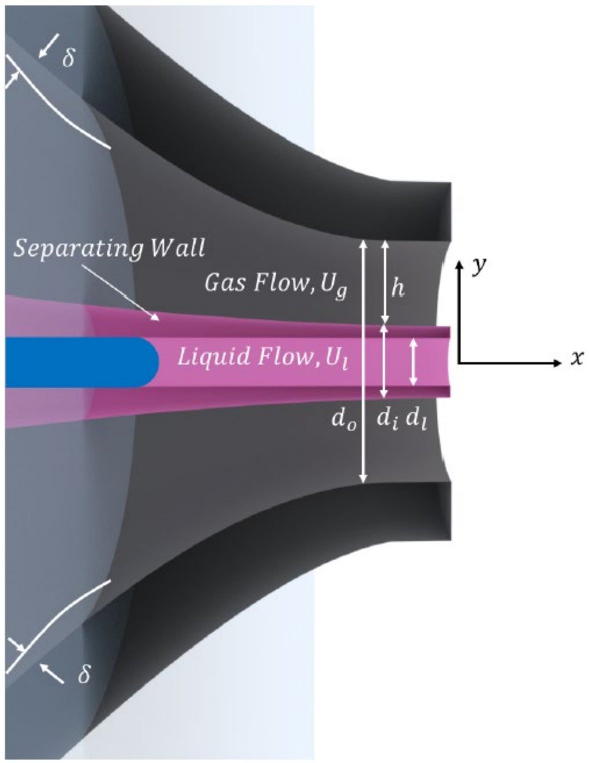


Machicoane and Aliseda (2017). Experimental Characterization of a Canonical Coaxial Gas-Liquid Injector, ILASS-Americas 29th Annual Conference, Georgia Tech, May

Co-Axial Jet

- **MURI Injector**



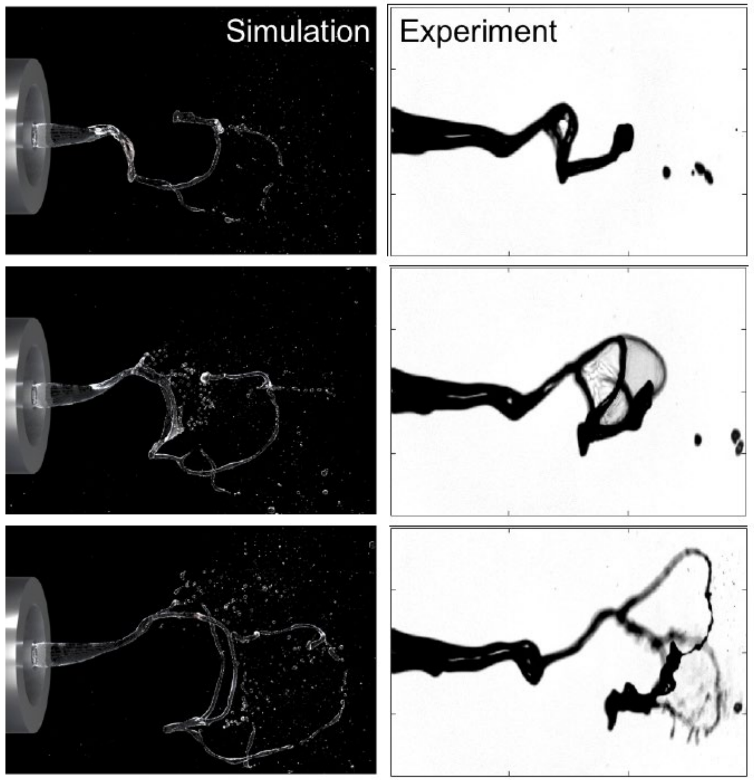


Case 1

Re_{gas} = 17,500 q = 5.8

Re_{liq} = 1000

We_{Δ} = 4.54 Δ = 100 micron



(a) Case 1

Machicoane and Aliseda (2017). Experimental Characterization of a Canonical Coaxial Gas-Liquid Injector, ILASS-Americas 29th Annual Conference, Georgia Tech, May

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Spanning the Applications

- Plain jet
- Simplex Atomizer
- **Fan Spray**

- Co-axial gas-liquid
- Plain jet in crossflow?
- Airblast

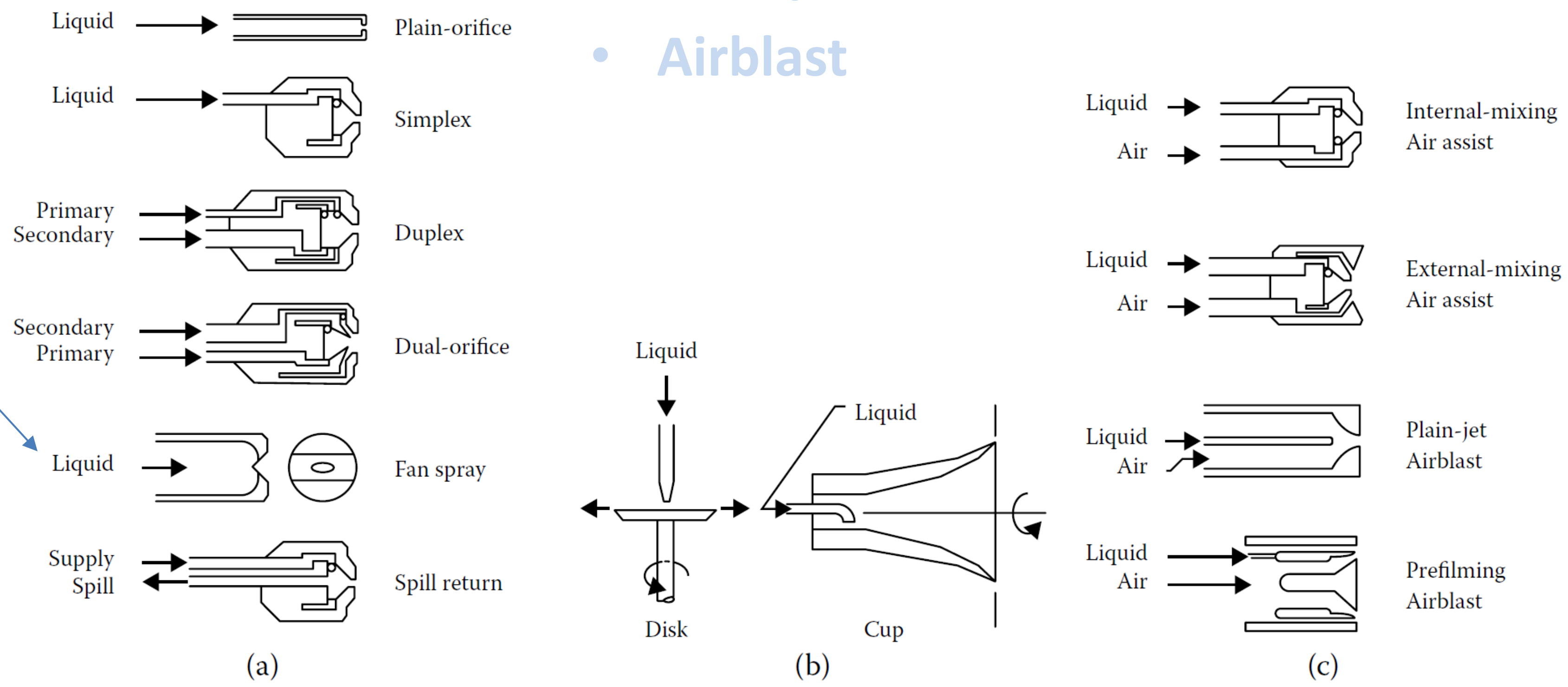


FIGURE 1.2
(a) Pressure atomizers, (b) rotary atomizers, and (c) twin-fluid atomizers.

Fan Spray

- **No "consensus" device at this point**
  - **Potential candidate is the TPU650050 flat spray nozzle from Spraying Systems Co**
    - ✓ **225 mL/min @ 4 bar**

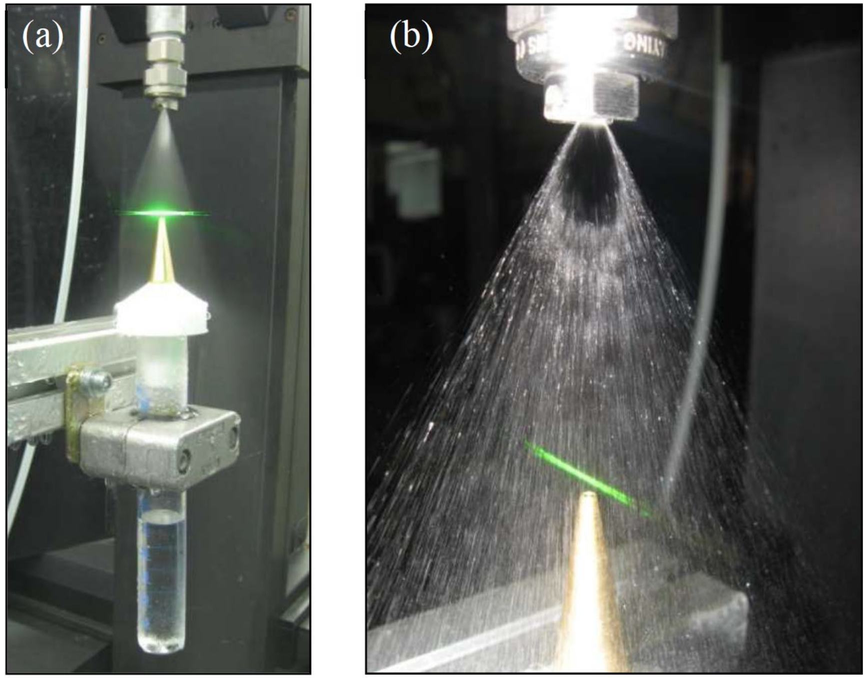


FIG. 1: (a) CT device. (b) CT sharp-edge 2 mm diameter opening

Bade, K.M. and Schick, R.J. (2011). Phase Doppler Interferometry Volume Flux Sensitivity to Parametric Settings and Droplet Trajectory, Atomziation and Sprays, Vol 21 (7), pp 537-551

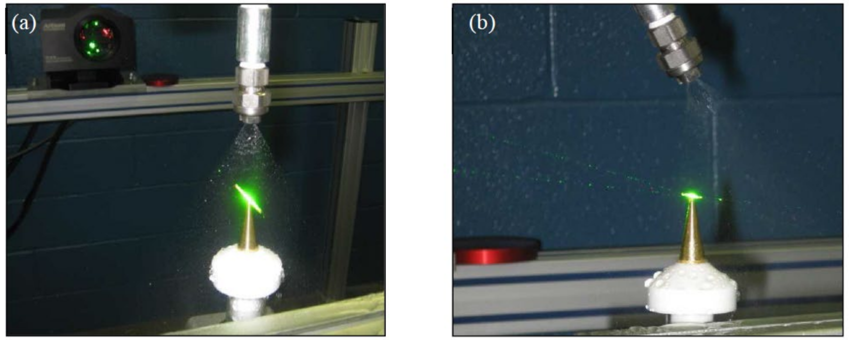


FIG. 12: (a) Standard nozzle setup (CT_1 and PDI_1) and (b) aligned nozzle setup (CT_2 and PDI_2).

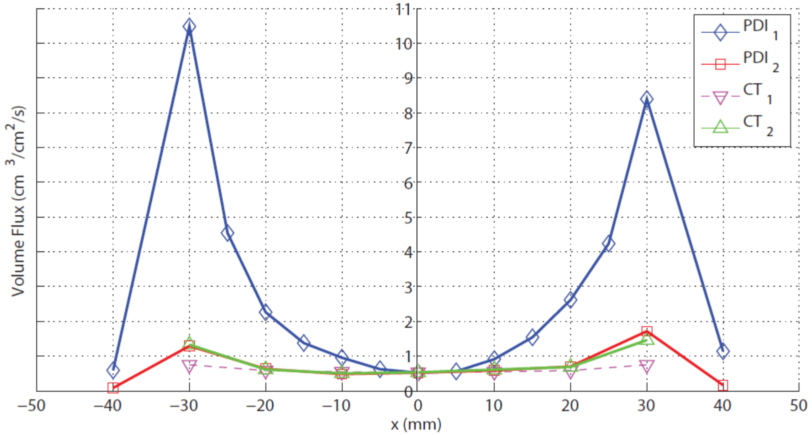


FIG. 14: Volume flux at $y = 0$, PDI and CT results.

Spanning the Applications

- Plain jet
- Simplex Atomizer
- Fan Spray

- Co-axial gas-liquid
- **Plain jet in crossflow?**

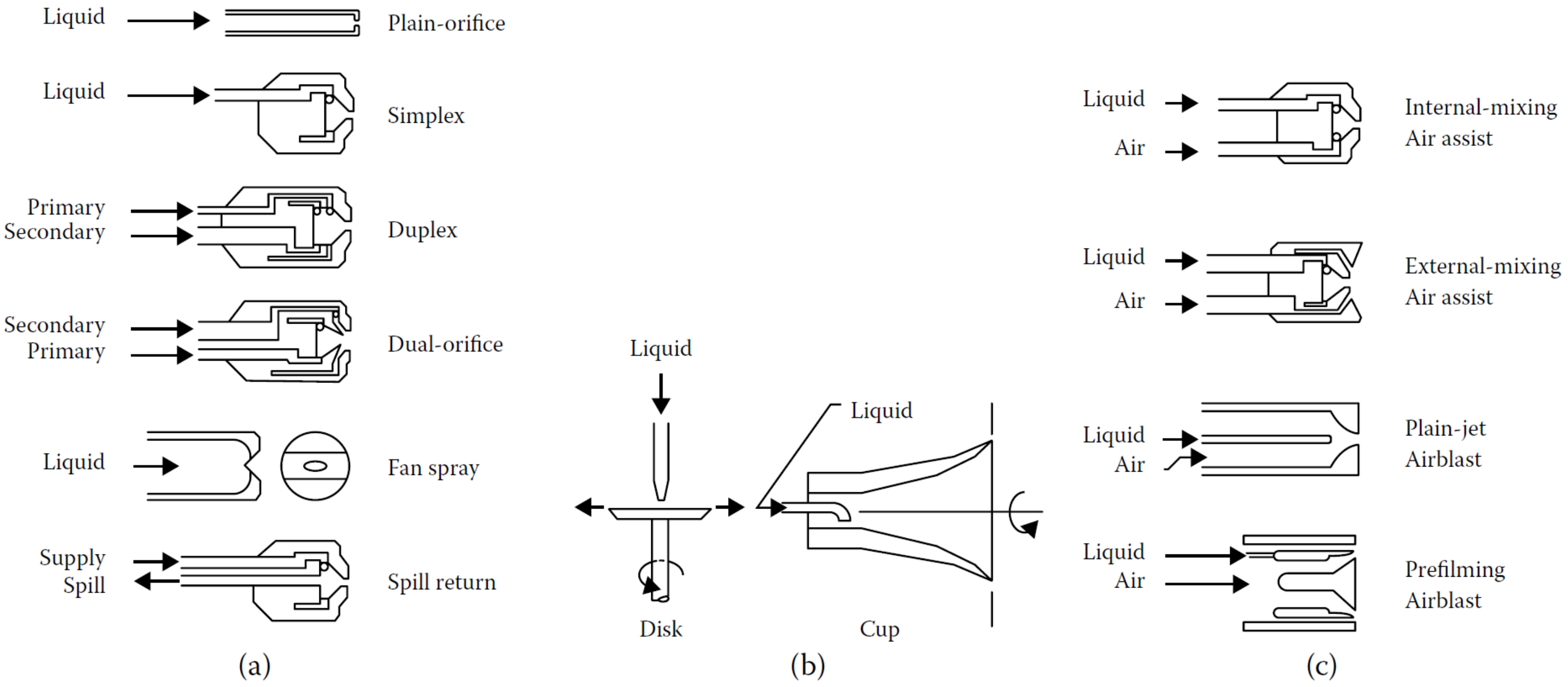
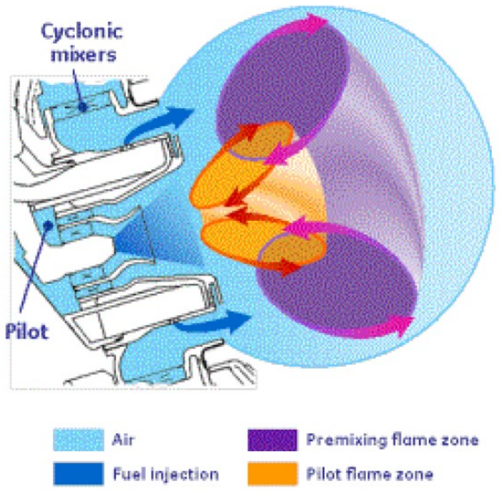


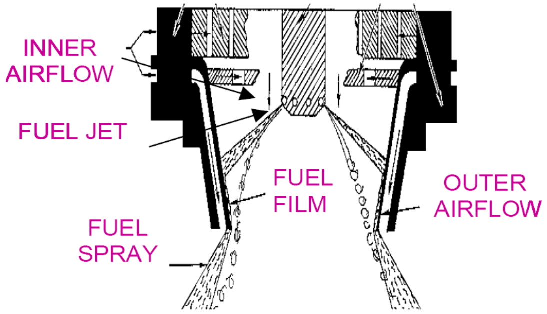
FIGURE 1.2
(a) Pressure atomizers, (b) rotary atomizers, and (c) twin-fluid atomizers.

Plain Jet in Crossflow

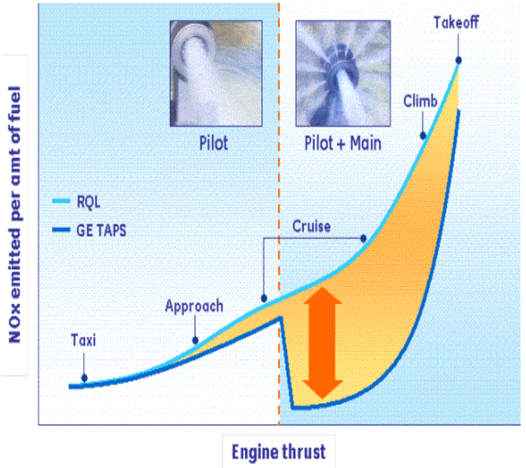
- **Applications**



Foust, et al. 2012
TAPS



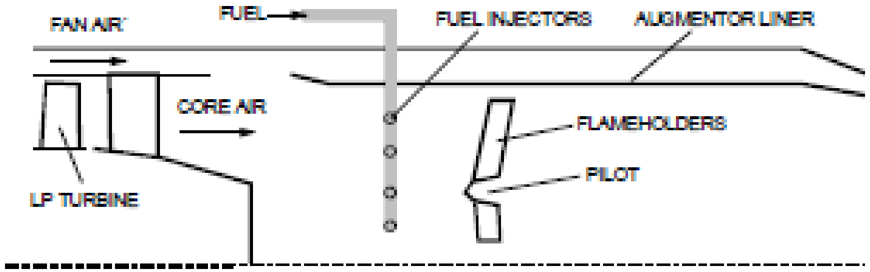
McKinney et al., 2007
Pratt & Whitney High Shear Injector



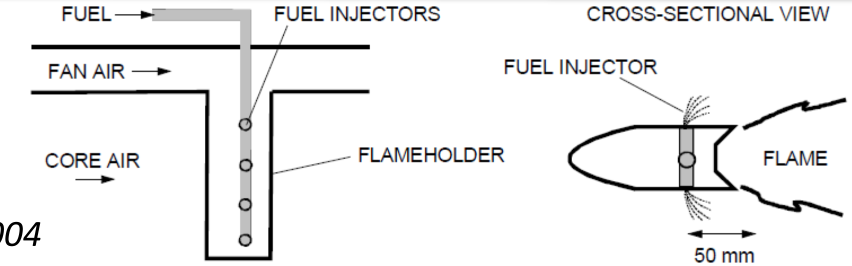
Plain Jet in Crossflow

- **Applications**

"Legacy"



Close Coupled



Lovett, et al., 2004

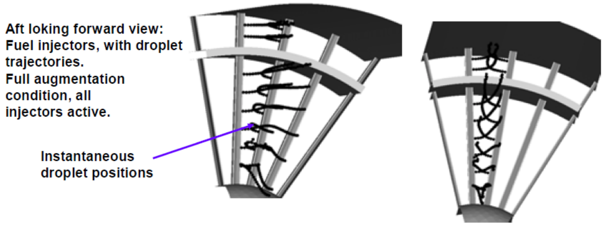


Figure 8. Views of the liquid spray droplet trajectories.

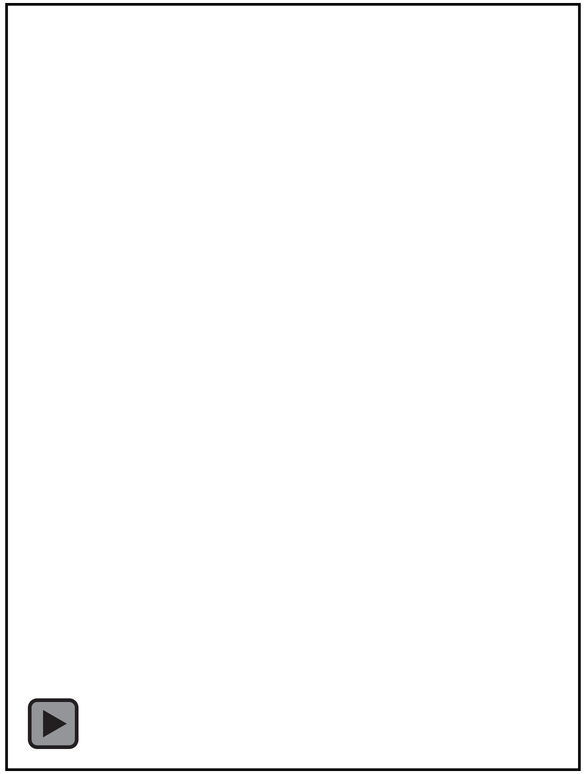
Ibrahim, 2006

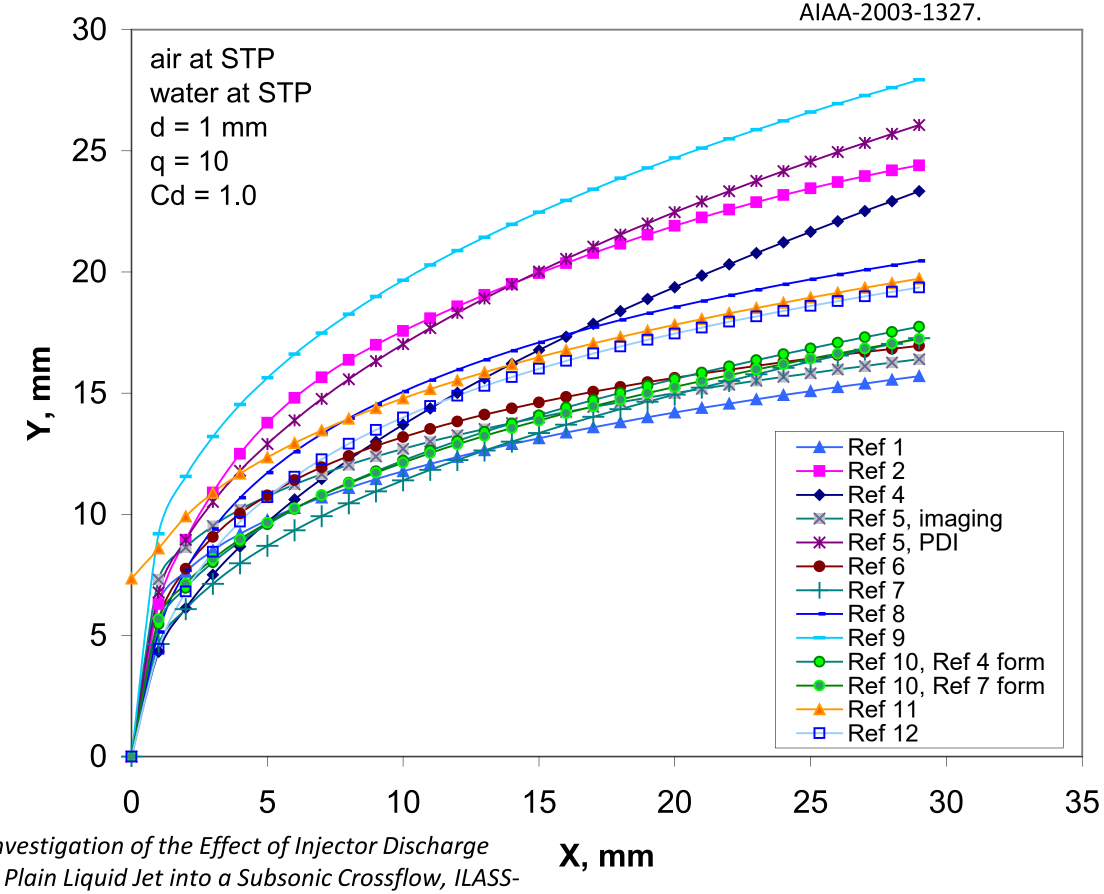
Plain Jet in Crossflow

- **Numerous correlations for penetration**

$$\frac{y}{d}=2.63\,q^{0.442}\left(\frac{x}{d}\right)^{0.39}We^{-0.088}\left(\frac{\mu_l}{\mu_{H_2O}}\right)^{-0.027}$$

Stenzler, et al., (2003). Penetration of Liquid Jets in a Crossflow, AIAA-2003-1327.

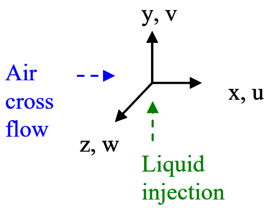




$$\frac{y}{d}=1.37\left(q\frac{x}{d}\right)^{0.5}$$

Wu, et al., (1998)

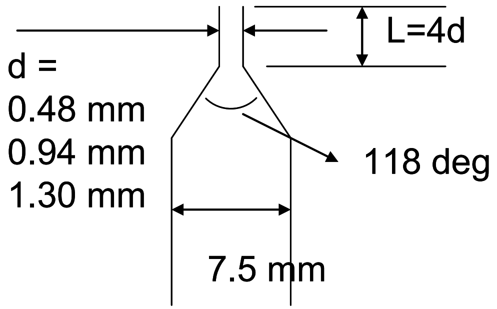
Why are the differences so large?
--concern for design tools



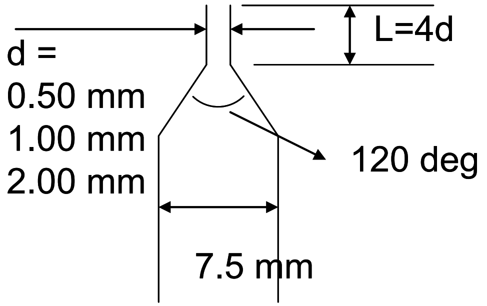
Brown and McDonell (2007). Investigation of the Effect of Injector Discharge Coefficient on Penetration of a Plain Liquid Jet into a Subsonic Crossflow, ILASS-Americas 2007, Chicago, IL, May

Plain Jet in Crossflow

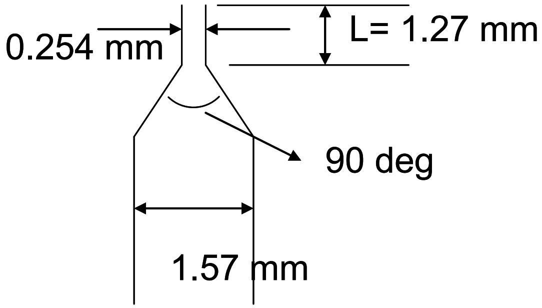
- **10. Brown & McDonell, 2006**
  - **L/D = 4**
  - **118 deg taper**

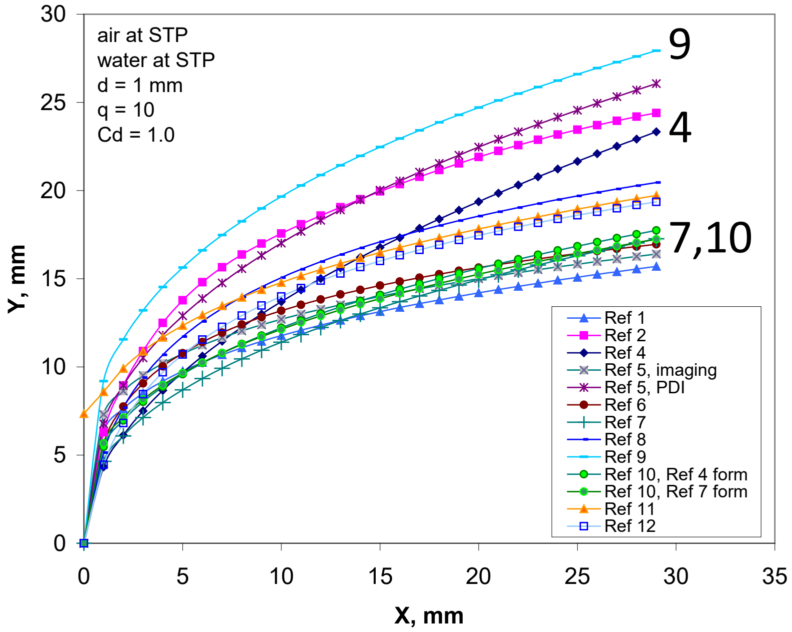


- **4,9. Wu, et al., 1997**
  - **L/D = 4**
  - **120 deg taper**



- **7. Stenzler, et al., 2003**
  - **L/D = 5**
  - **90 deg taper**





Plain Jet in Crossflow

- **10. Brown & McDonell, 2006**
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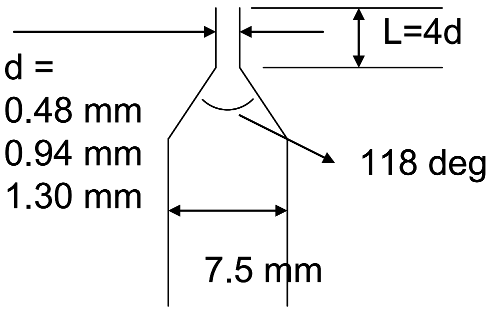
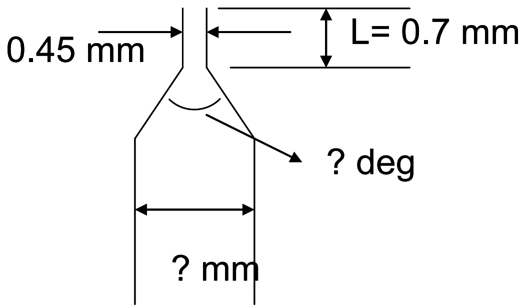
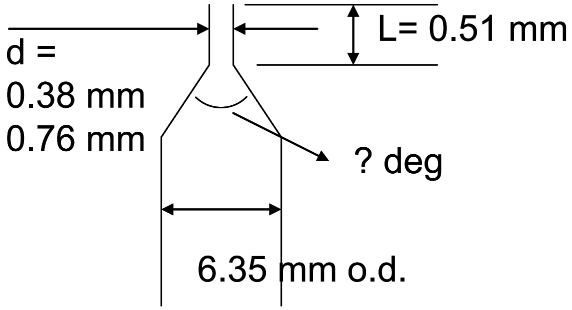
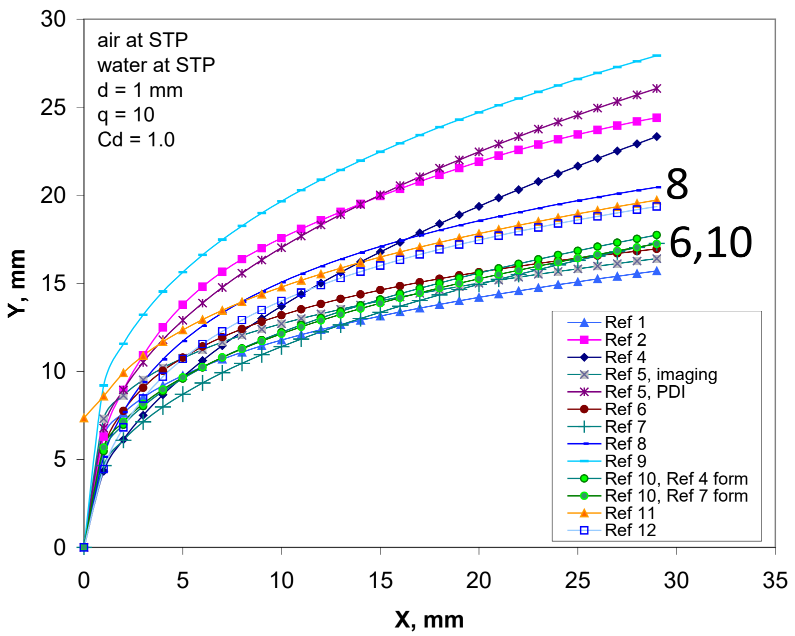


- **6. Becker & Hassa, 2002**
  - **L/D = 1.56**
  - **Taper = ?**



- **8. Tambe, Jeng, et al., 2005**
  - **L/D = 1.33, 0.67**
  - **Taper = ?**





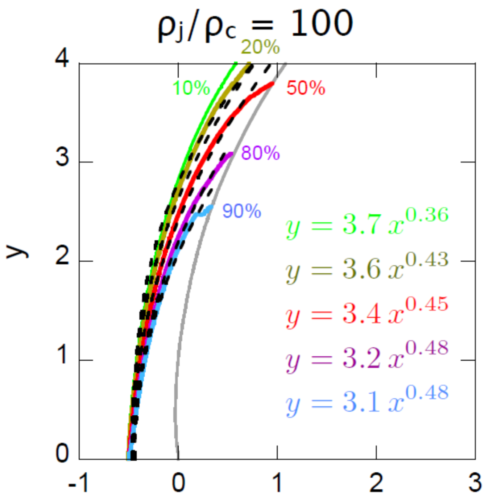
Plain Jet in Crossflow

- **Related to Internal Geometry….**
  - **Momentum Flux**

$$\frac{y}{d} = 1.37\left(q\frac{x}{d}\right)^{0.5}$$

$$q = \frac{\rho_j U_j^{\,2}}{\rho_c U_c^{\,2}}$$

  - **Literature historically defines liquid jet velocity is determined from the ratio of the volumetric flow to injector orifice cross sectional area**
    - ✓ Apparently for "convenience"?
    - ✓ Cd is a strong function of internal geometry
    - ✓ Cd directly affects Uj
  - **Subtleties relative to defining edge**
    - ✓ Herrmann illustrated numerically→
  - **Crossflow Boundary Layer?**
  - **Test Section Cd values?**



mid injector cut planes

Wu et al.: $y = 3.5\,x^{0.50}$

Stenzler et al: $y = 3.6\,x^{0.39}$

Plain Jet in Crossflow

- **Development of a Portable "Standard Test Rig" for JIC studies**
  - **50 mm x 50 mm**
  - **Details about injector interior set**
  - **Details about crossflow boundary layer set**

Becomes somewhat like ECN in that not only is the injector standardized, but so is the entire environment ($$)

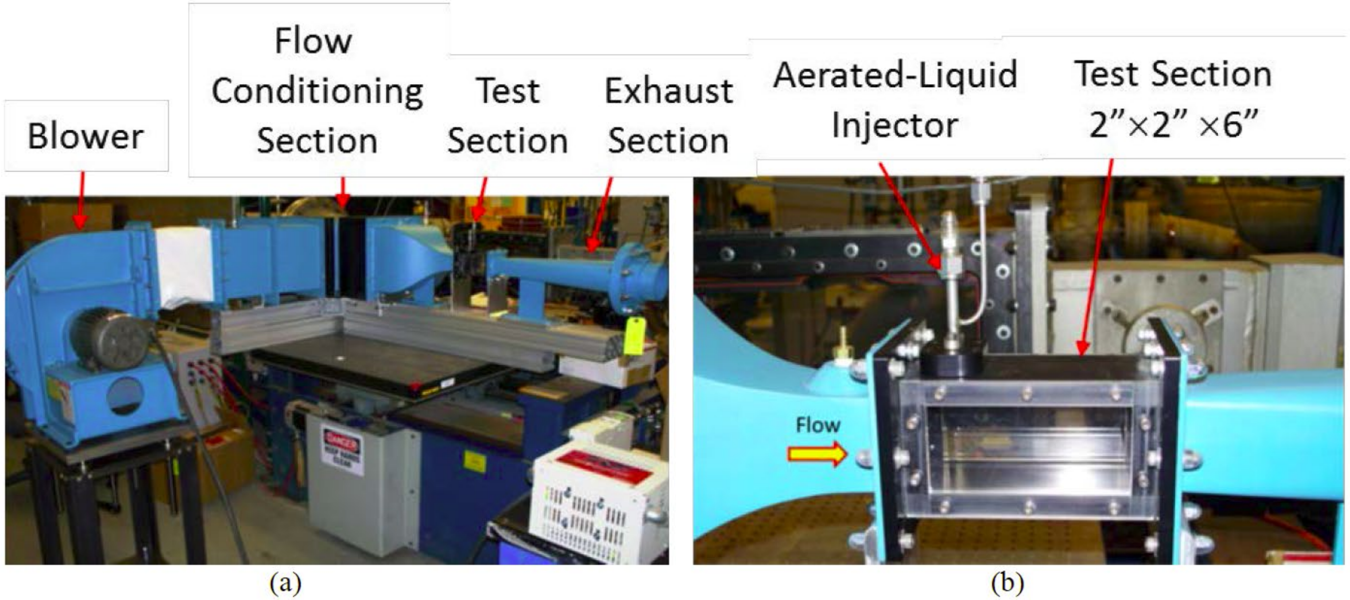


Figure 1. (a) Photograph of the portable wind tunnel with main components identified, (b) Photo graph of the test section with clear sidewalls for visual observation and optical measurement (injector at the top for illustration).

- At a minimum, can an acceptable internal geometry be established?
- Role of surface finish/manufacturing?

Lin, K-C., Carter, C. Peltier, S., Kastengren, A., and Lai, M.-C. (2016). Characterization of Liquid Jets in Subsonic Crossflows using X-Ray Radiography, ILASS-Americas 2016, Dearborn, MI, May