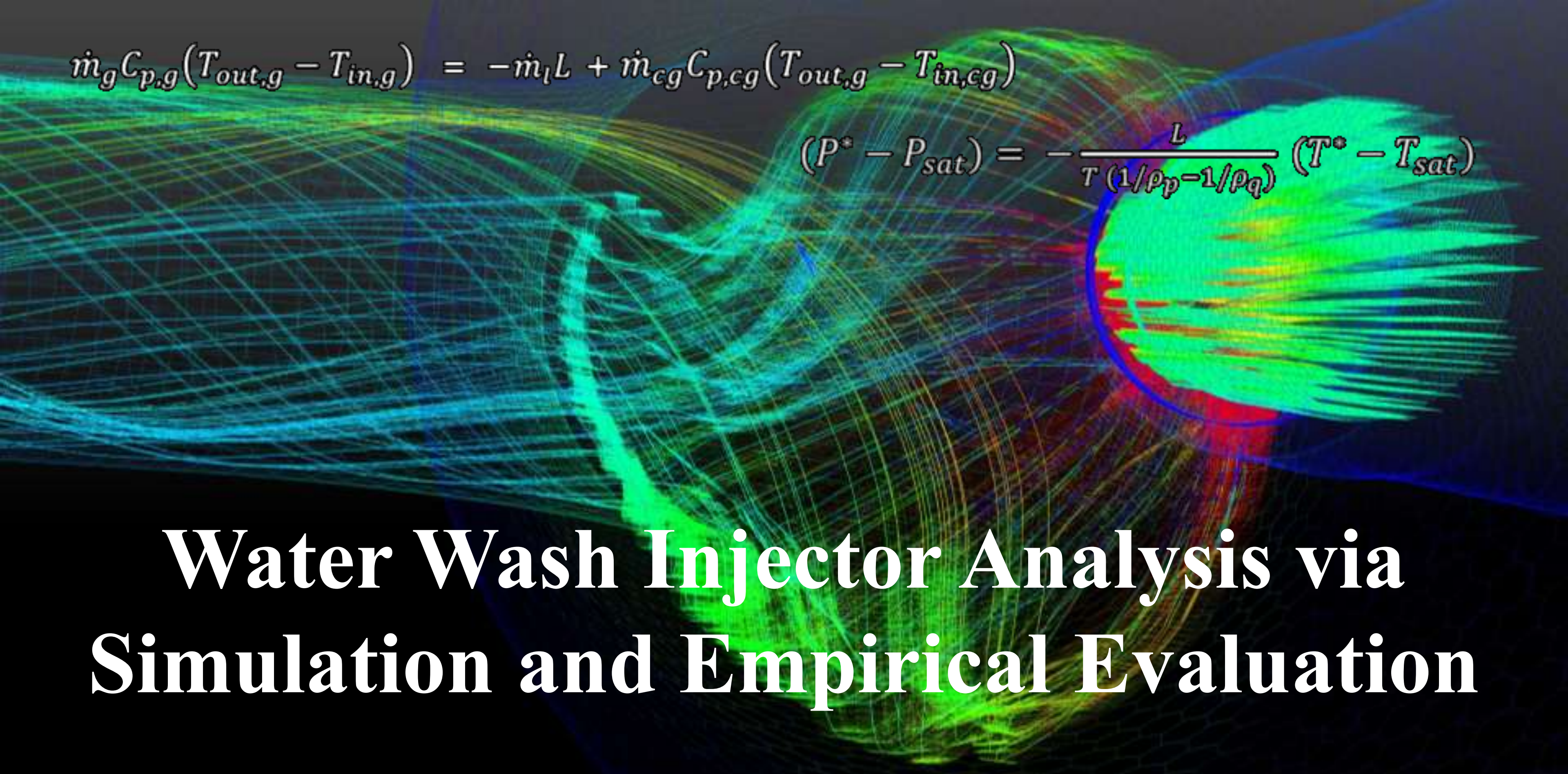

$$\dot{m}_g C_{p,g}(T_{out,g} - T_{in,g}) = -\dot{m}_l L + \dot{m}_{cg} C_{p,cg}(T_{out,g} - T_{in,cg})$$

$$(P^* - P_{sat}) = -\frac{L}{T\,(1/\rho_p - 1/\rho_q)}(T^* - T_{sat})$$

Water Wash Injector Analysis via Simulation and Empirical Evaluation

K. J. Brown, W. Kalata, R. J. Schick

Spraying Systems Co.

Spray Analysis and Research Services From Spraying Systems Co.

HYDROCARBON PROCESSING IRPC 2015

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Presentation Topics

- Company Overview
- Problem Description
- Methodology
- Results
- Conclusion and next steps

Who is Spraying Systems Co.

- **World Leader in Spray Technology**
  - Privately owned (Established 1937)
  - Headquarters in Wheaton, IL
- **Products**
  - Spray nozzles, related systems and accessories
  - Over 120,000 standard and 180,000 non-standard engineered products
- **Access to Market**
  - Global/Regional engineering and manufacturing
  - 85 local sales engineering offices around the world
- **Value added**
  - Recognized global brand for spray technologies
  - Quality, service, support, engineered solutions
  - Serve 50 major industrial markets

Spraying Systems Middle East

SSME Office

Dubai Silicon Oasis, Light Industrial Units, Office No. 07

P.O. Box 341187

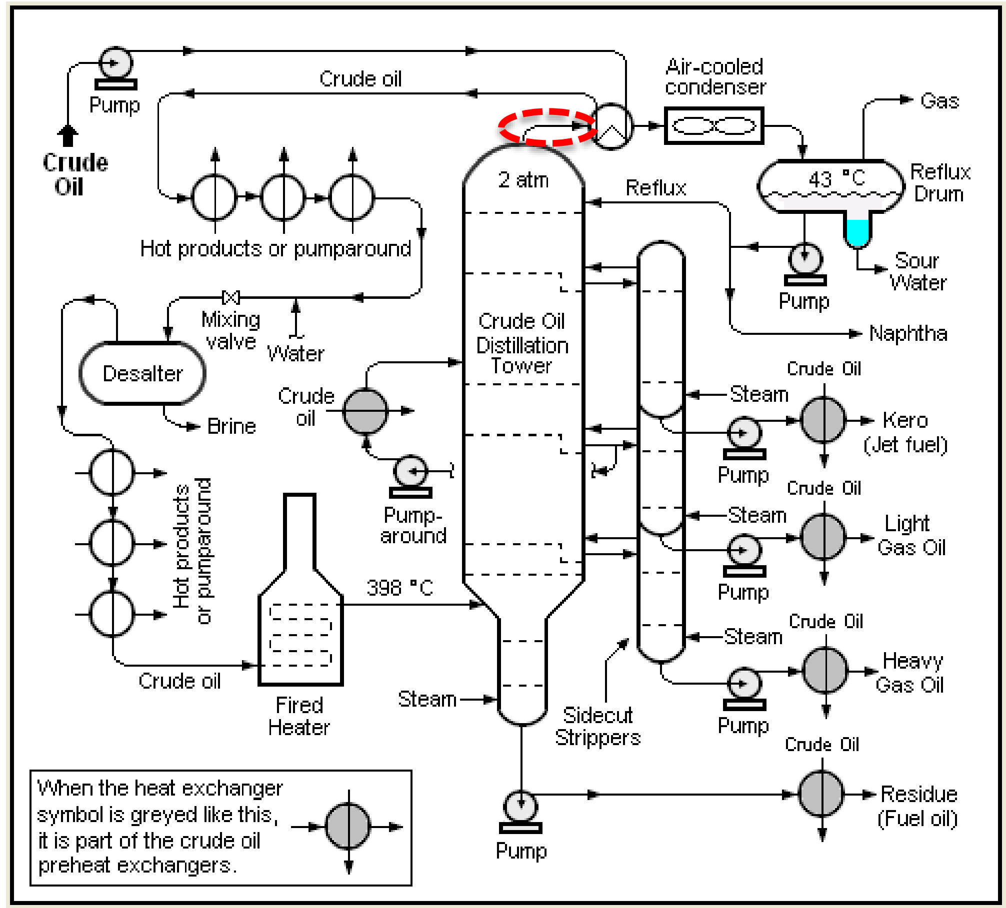
Dubai, United Arab Emirates

Water Wash Background[1]

Crude Unit Column Overhead – Corrosion

Water is usually injected in the overhead piping to:

- Help quench and scrub the overhead vapors
- Dilute acids formed
- Prevent any salts or acids from forming in the system

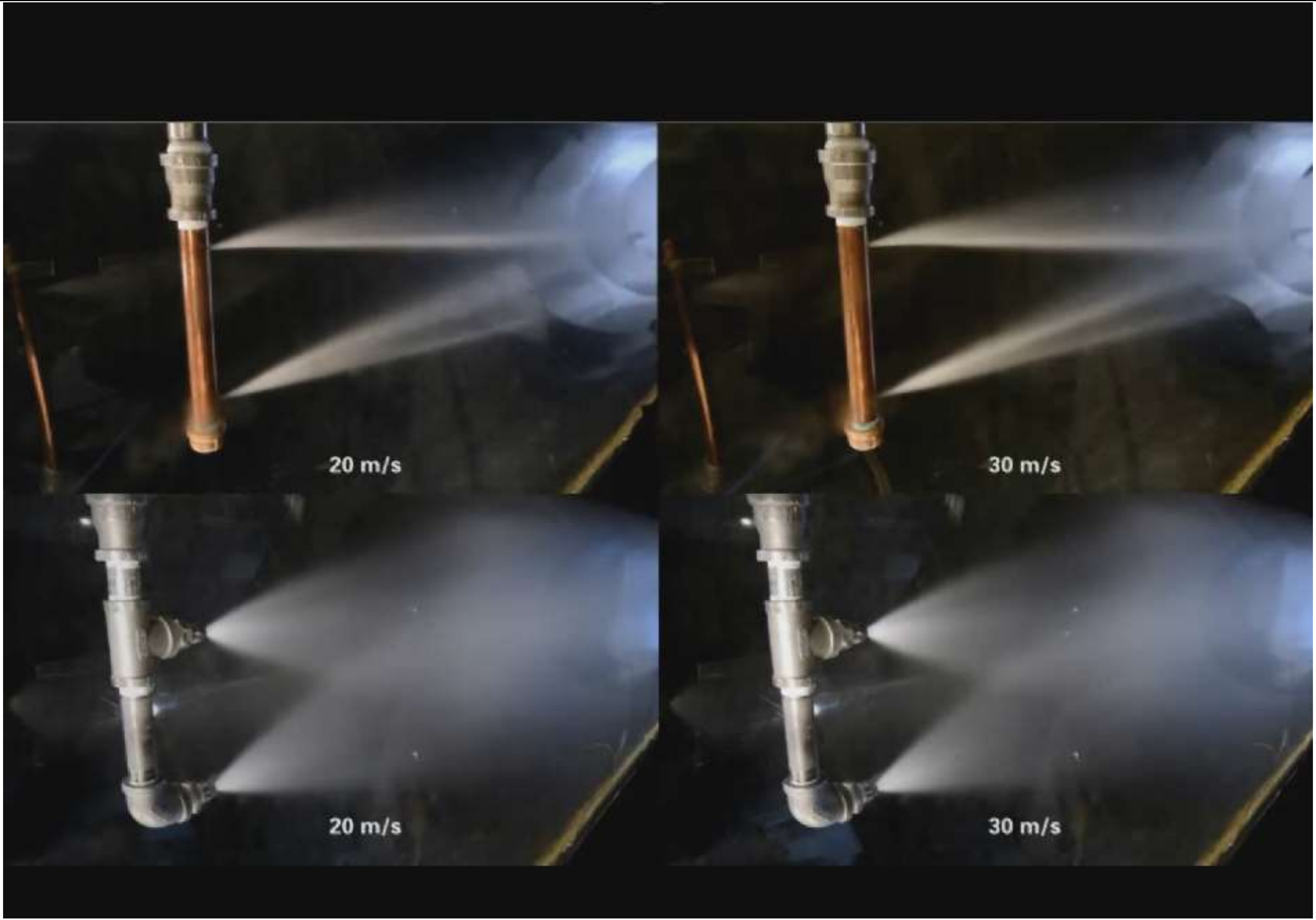


Water Wash Background[2]

- Even distribution of wash water increases the effectiveness of a water-wash system.
- Interaction of a spray plume in the environment determines the level of liquid/gas mixing and absorption effectiveness.
- Traditional methods rely of using simple Quills
  - Single/Dual Hole Design
  - Slot Design

- Often ineffective in areas where critical control is needed
- Introduction of Spray Nozzle Injectors significantly improves the process

Visualization



Water Wash Background

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- Even distribution of wash water increases the effectiveness of a water-wash system.
- Interaction of a spray plume within a confined cross-flow environment controls the level of liquid gas mixing and absorption effectiveness.
- The primary focus of this study is to define the distribution of injected water wash downstream of the injection point.
- Modeling is used in environments that are difficult to access, validation is necessary to be sure injector recommendations are accurate and optimized.

Methodology

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Validation process using experiments and modeling - used to evaluate spray performance of different nozzles.

- **Experiments**
  - Laser Sheet Imaging (LSI)
    -- spray shape, size and distribution characteristics
  - Phase Doppler Interferometer (PDI)
    -- drop size, velocity, angle of trajectory and spray volume
  - Wind tunnel

Test data is input for Modeling as initial conditions

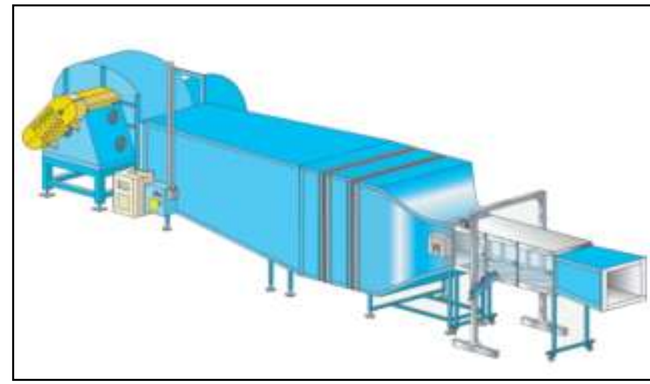
Validates results/experiments

- **Modeling (CFD)**
  -- spray simulation (custom spray injection methods)
  -- in situ data for engineering assessment in actual region

Empirical Setup

- **Large capacity Wind Tunnel, Ambient air**

- **Modified Test Section**
  - Ø40cm x 2.75m, with Optical access

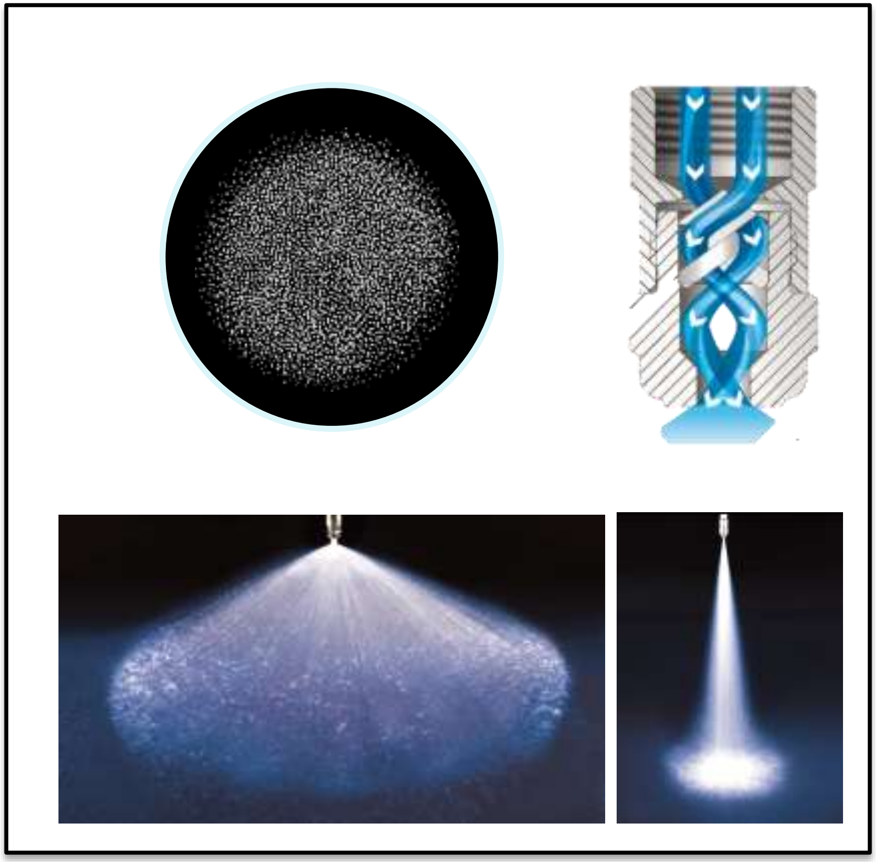


- **Nominally Uniform Airflow**
  - Operated at 20m/s and 30m/s

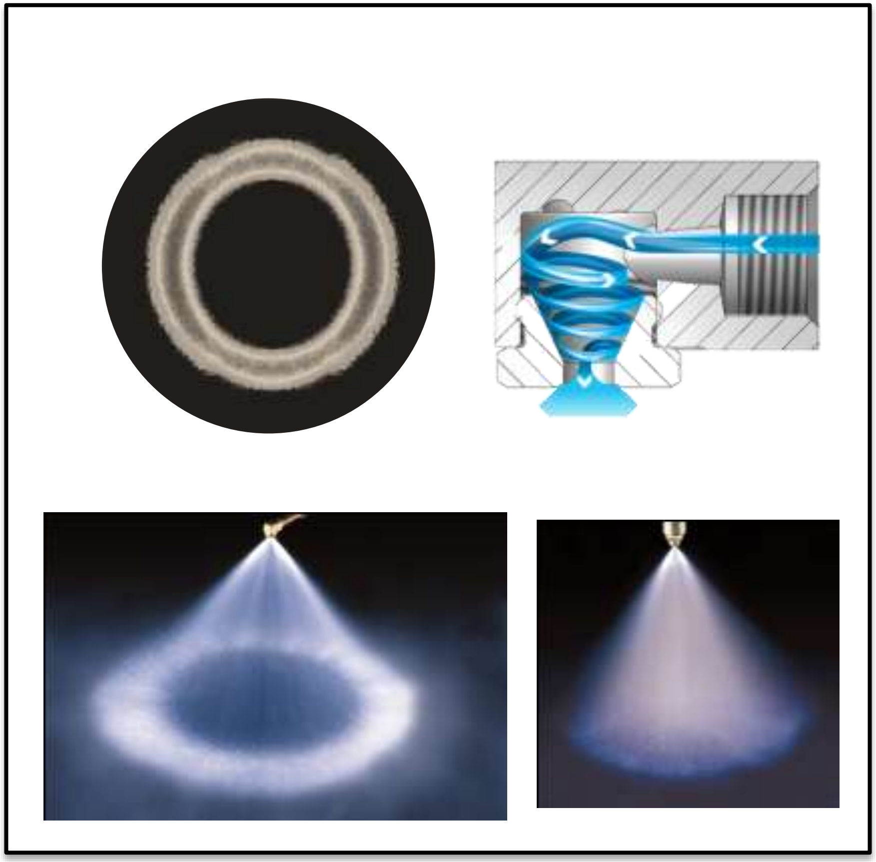
- **Injectors** (Flow Rate = 19LPM)
  - Hollow cone – 3/8BX-15
  - Full cone – 3/8GA-15
  - Dual Full cone – 1/4HH-6.5

Injectors

Full cone

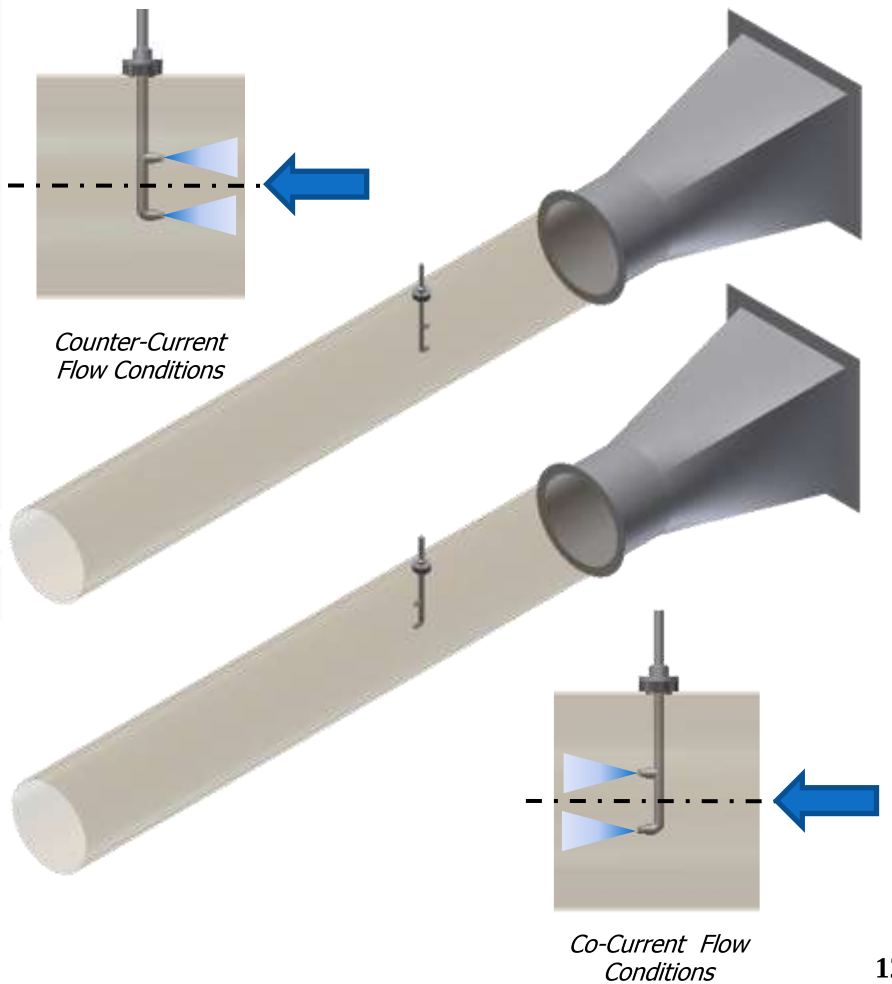


Hollow cone



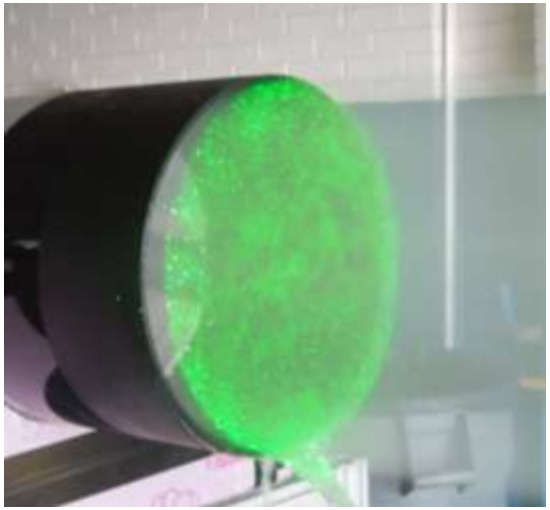
Flow Conditions

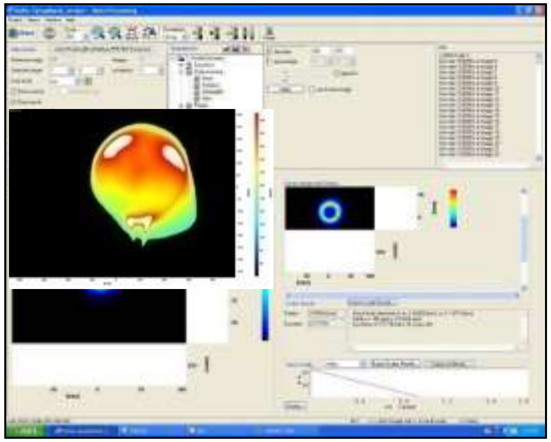
- **Flow Direction (injector relative to gas)**
  - Co-current
  - Counter-current
- **Gas Velocity**
  - ↑ from previous study
- **Injector Type**
  - Flow ↓ from previous study



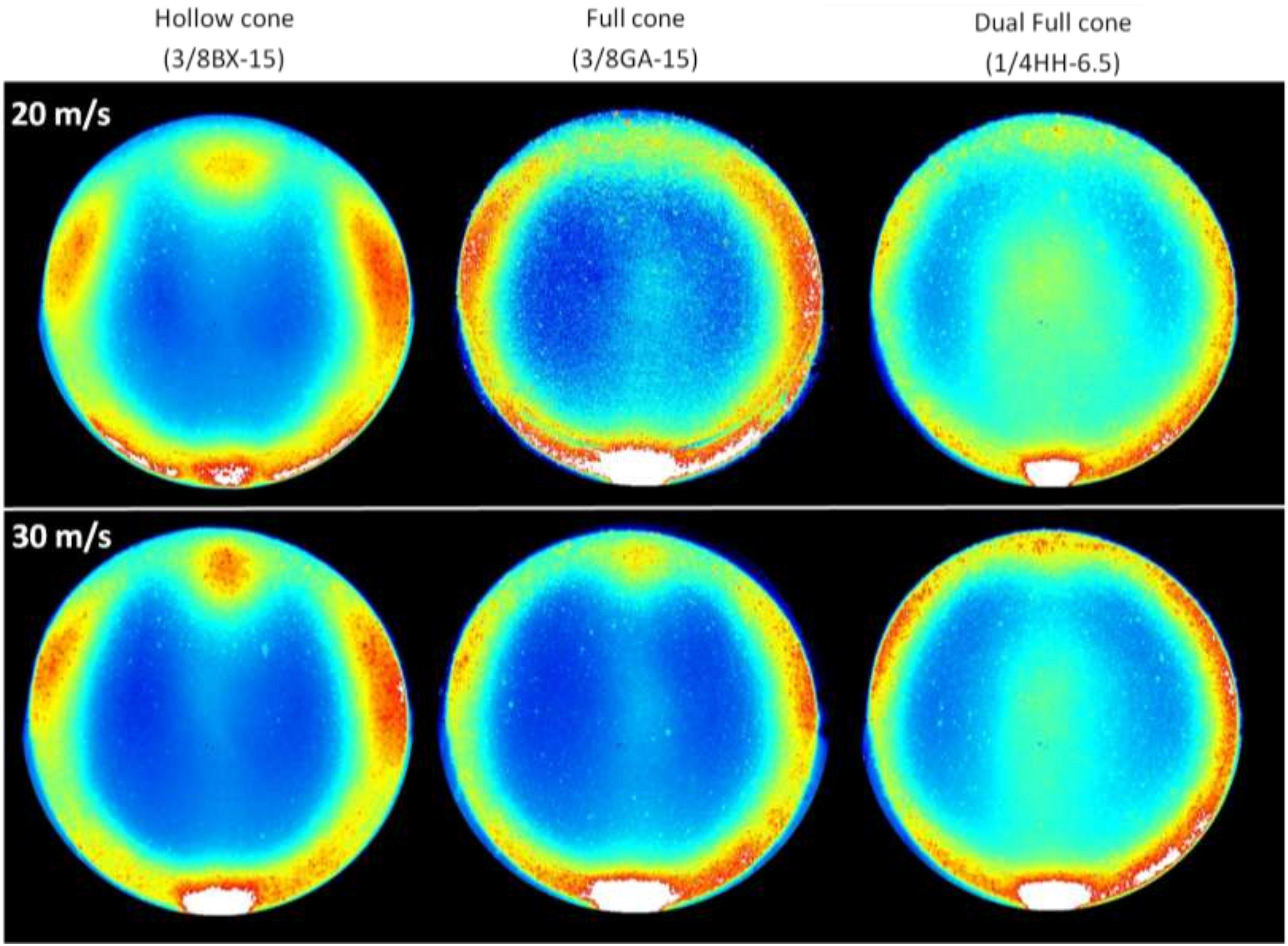
Experimental Setup – Spray Distribution Acquisition

- **Laser Sheet Imaging (LSI)**
  - LaVision GmbH
- **Orientation**
  - Mounted at exit of wind tunnel
  - Vertical and Horizontal
    - 2D measurement of spray pattern
    - Time dependant fluctuations
- **Light Intensity – Spray uniformity**
  - Mie Scattering

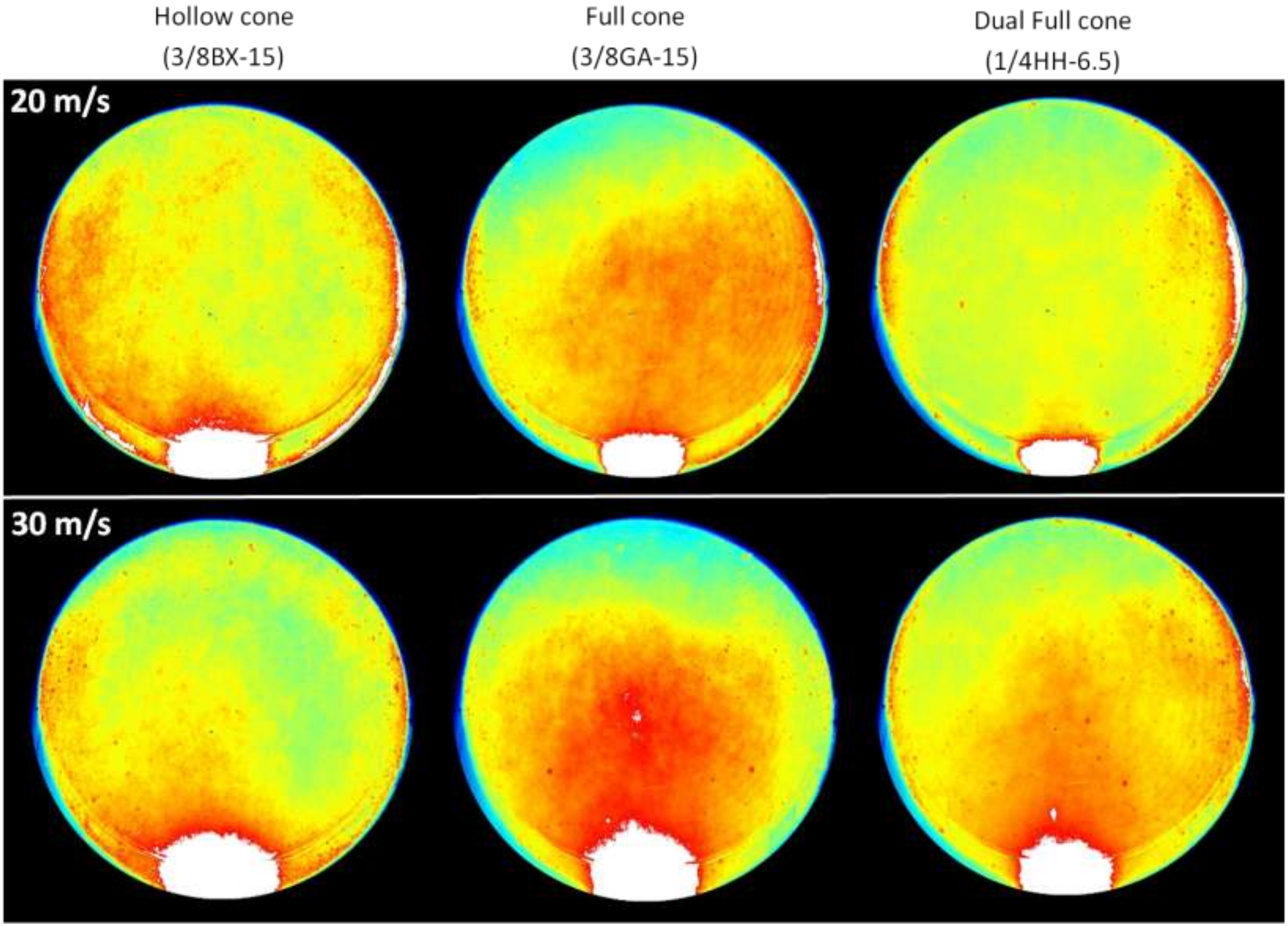




Spray Distribution – co-current

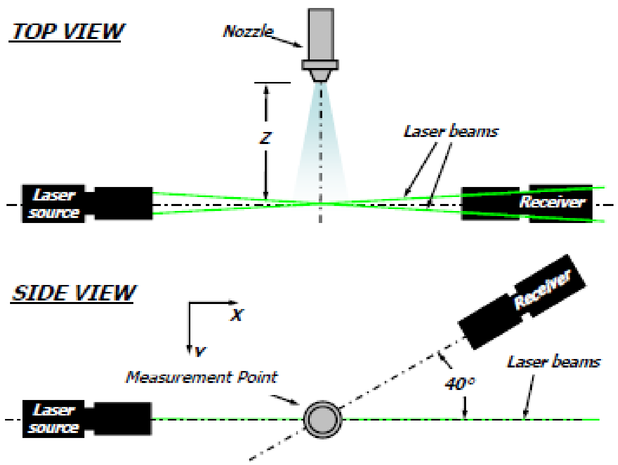


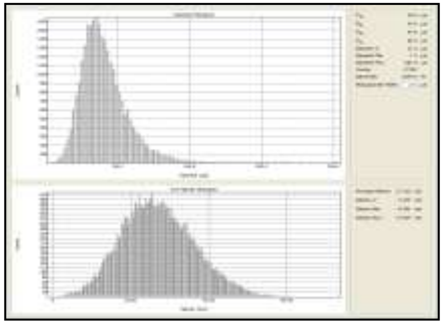
Spray Distribution – counter-current



Experimental Setup – Drop Size Acquisition

- **Phase Doppler Interferometer (PDI)**
  - Artium Technologies Inc.
  - PDI-200MD
- **PDI Orientation**
  - Mounted at exit of wind tunnel
  - Vertical and Horizontal Traverse
    - y – 2cm measurement resolution
    - z – 6cm measurement resolution
- **Drop Size Distribution**
- **Axial Velocity**

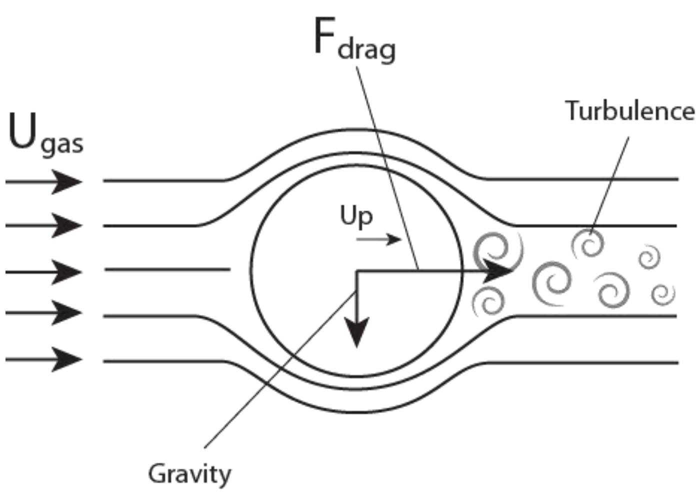


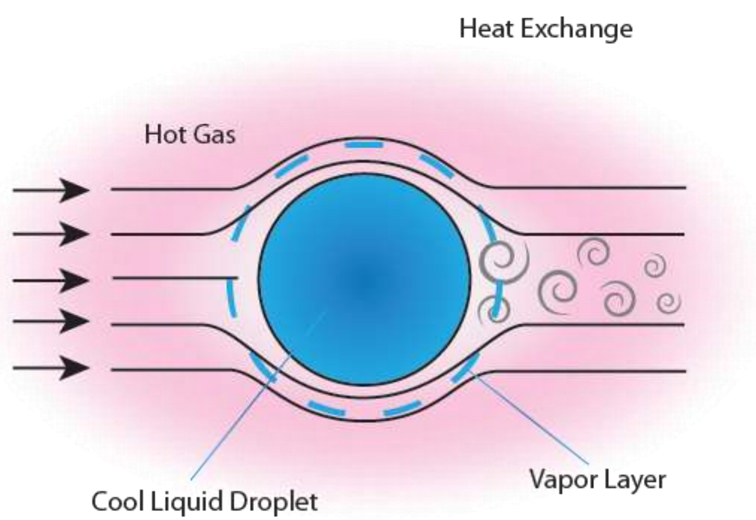


Drop Size Impact[1]

- **Has major impact in increase process effectiveness**

- **Effectiveness is increased because**
  - **Greater Surface Area →** increases contact area with gas stream
  - **More Uniform Distribution across Duct/Vessel →** increases interaction and uniformity of reaction

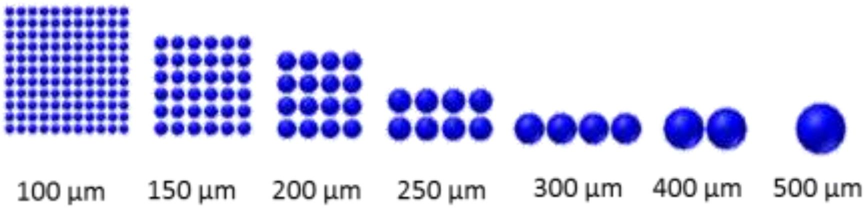




Drop Size Impact[2]

No. of Drops	Diameter (µm)	Volume (m^3)	Surface Area (m^2)	Percentage increase in Surface Area
1	500	6.54×10^{-11}	1.96×10^{-7}	--
120	100	6.54×10^{-11}	9.42×10^{-7}	484%

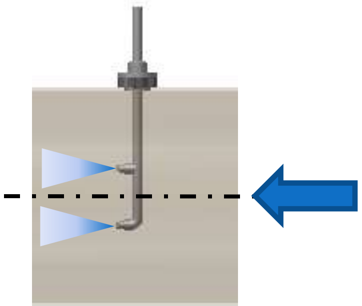
Heat/Mass Transfer & Chemical Reactions ~ Droplet Surface Area ($4\pi r^2$)



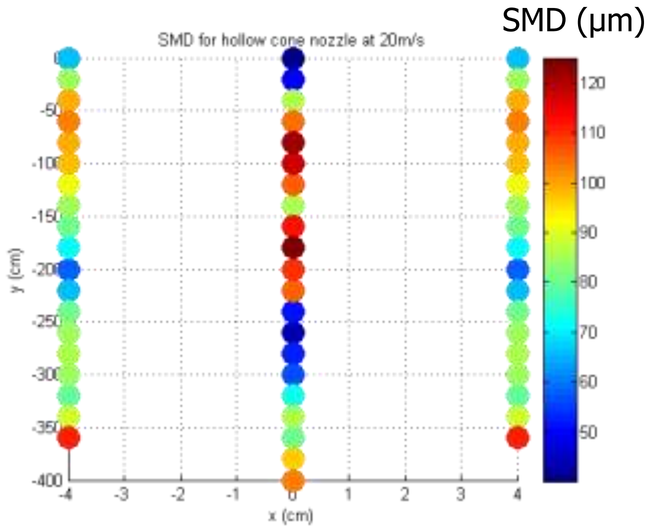
Results – Drop Size at 20m/s

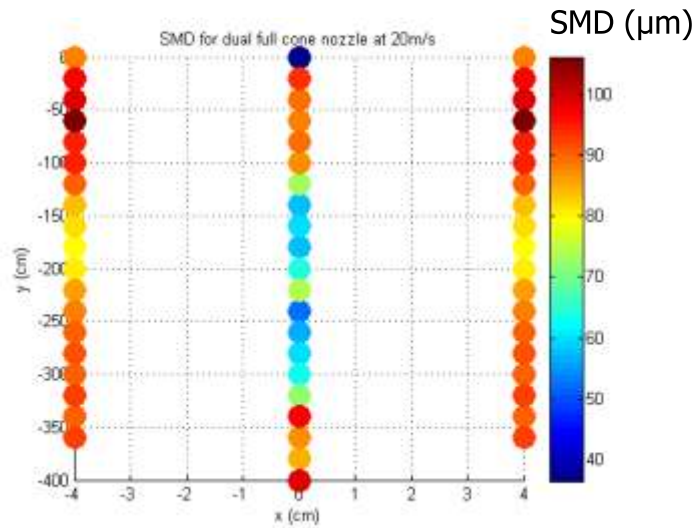
Hollow cone (3/8BX-15) | Dual Full cone (1/4HH-6.5)

Co-current

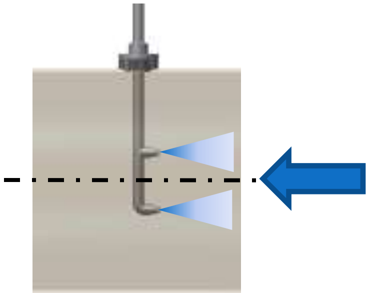


Co-Current Flow Conditions

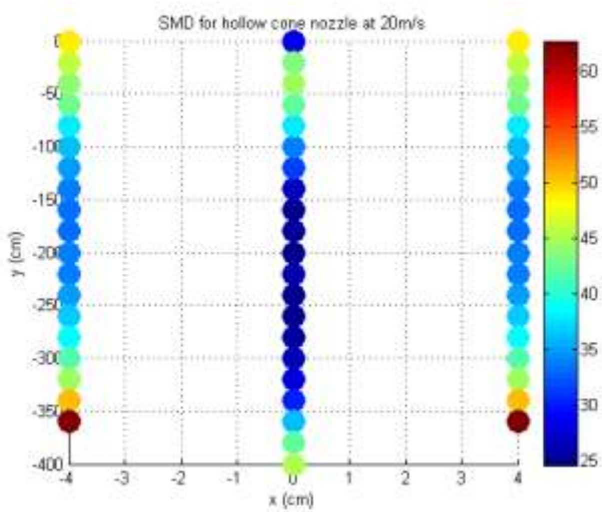


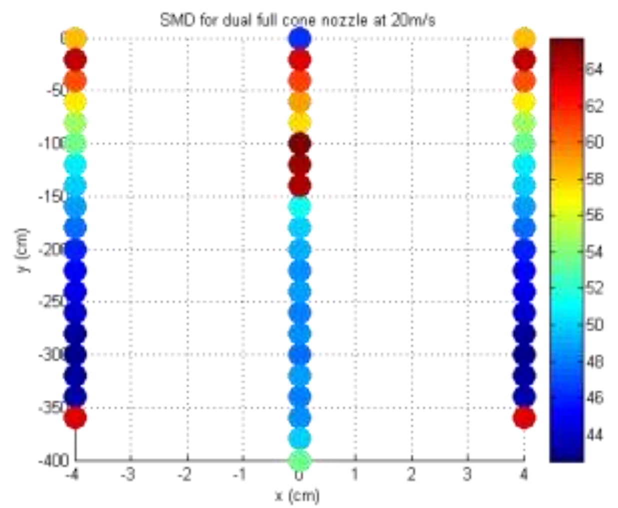


Counter-current



Counter-Current Flow Conditions

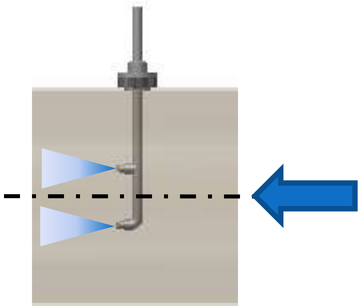




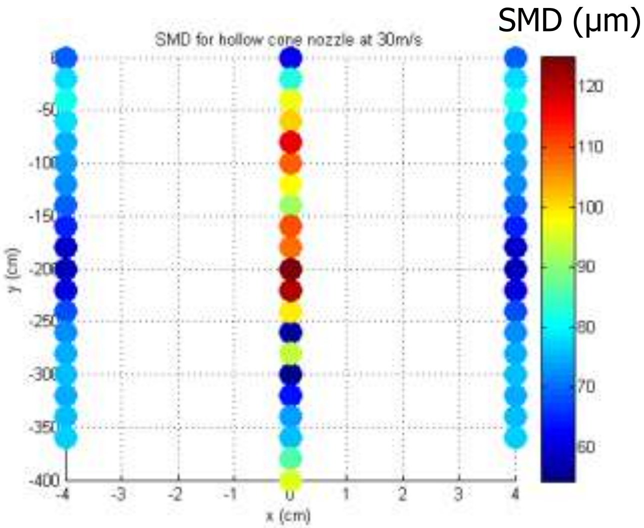
Results – Drop Size at 30m/s

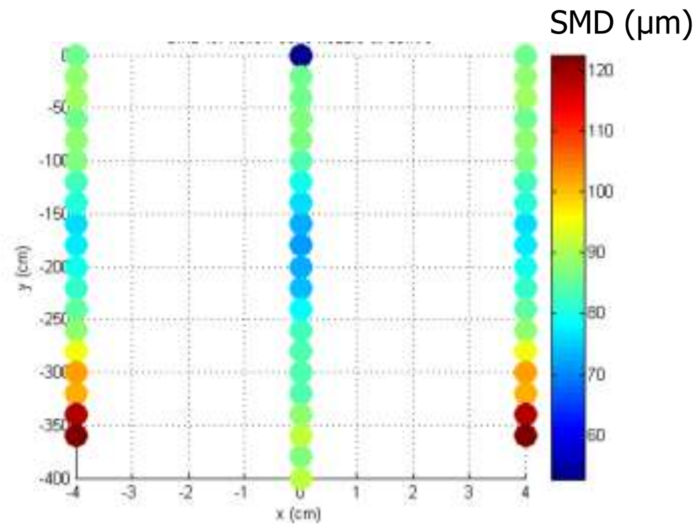
Hollow cone (3/8BX-15) | **Dual Full cone (1/4HH-6.5)**

Co-current

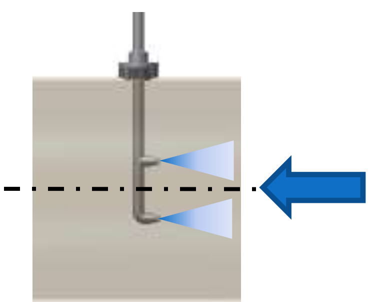


Co-Current Flow Conditions

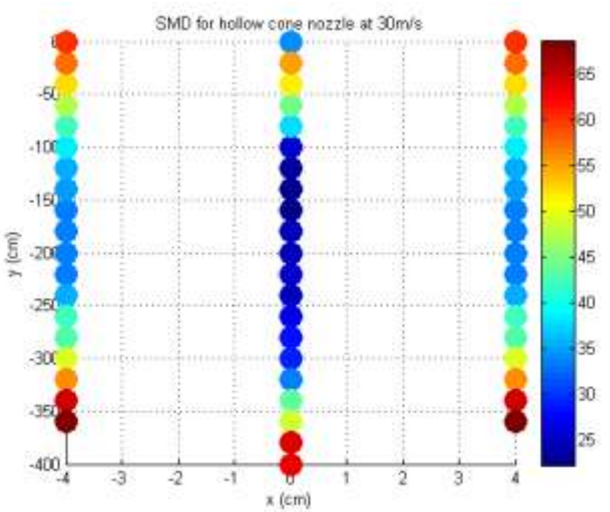


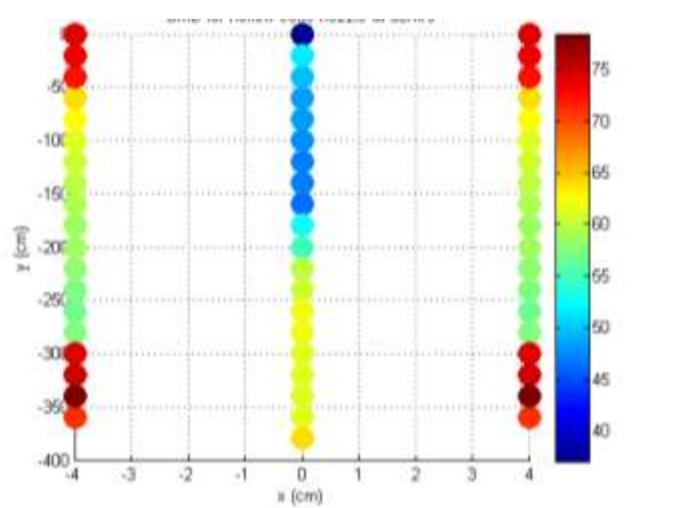


Counter-current

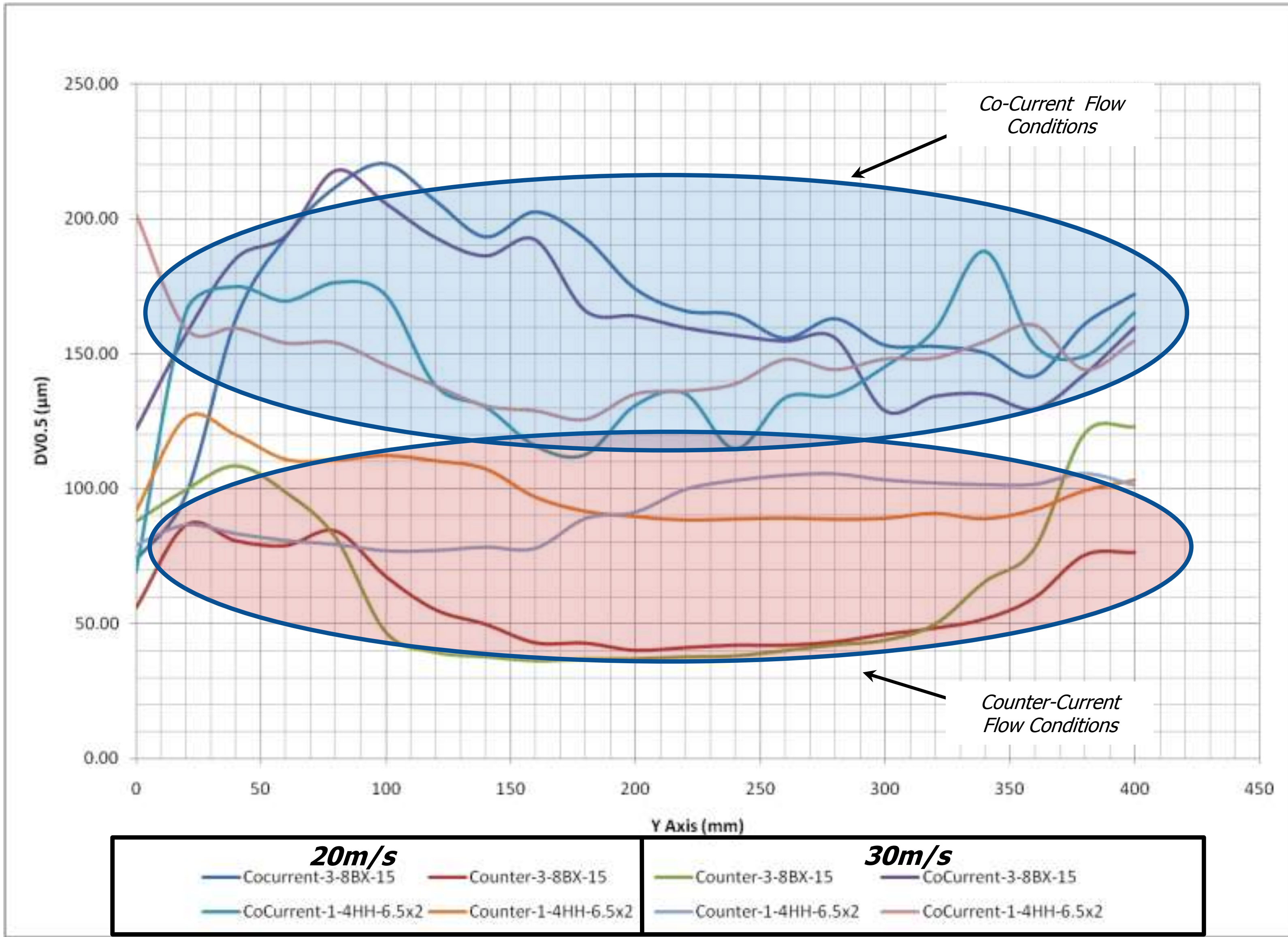


Counter-Current Flow Conditions





Drop Size – Summary



co vs. counter-current

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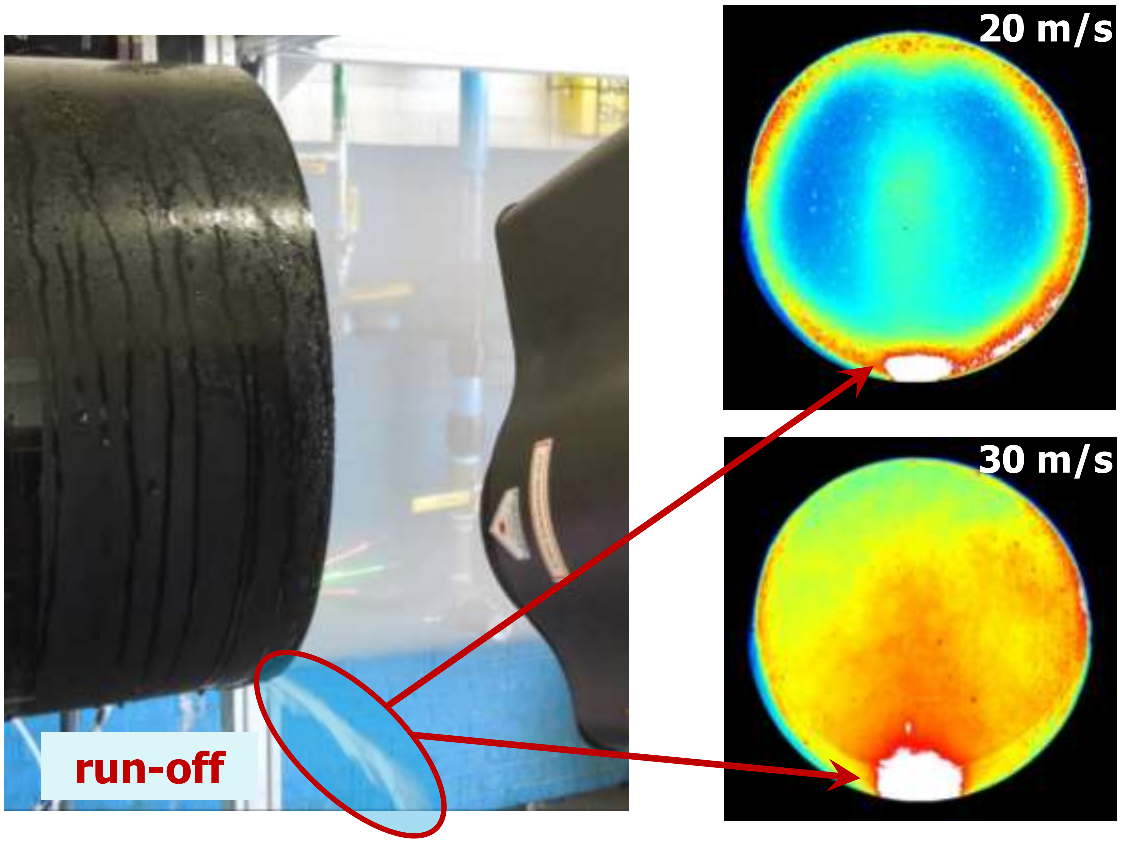
Run-off



Increasing run-off with counter-current flow and decreasing gas velocity

Industry Guidelines

- Inadequate (or low) Water Wash can be worse than no Water Wash:
  - Many of the salt deposits encountered in refining processes are hygroscopic, hence inadequate water washing can lead to severe localized corrosion in certain circumstances
- At least 25% of water injected should remain as liquid water

Injector Types & Runoff

		Case	1	2	3	4	5	6	7	8	9	10	11	12
Injector Type			HC	FC	2xFC	HC	FC	2xFC	HC	FC	2xFC	HC	FC	2xFC
Nozzle ID			3/8BX -15	3/8GA -15	1/4HH -6.5	3/8BX -15	3/8GA -15	3/8HH -6.5	3/8BX -15	3/8GA -15	1/4HH -6.5	3/8BX -15	3/8GA -15	3/8HH -6.5
Air Flow Conditions			co-current			co-current			counter-current			counter-current		
Air Velocity	V	m/s	20	20	20	30	30	30	20	20	20	30	30	30
Operating Pressure	ΔP	bar	9.31	9.44	13.44	9.31	9.44	13.44	9.31	9.44	13.44	9.31	9.44	13.44
Flow Meter	Q_{TOTAL}	lpm	18.9	18.9	18.9	18.[illegible]	[illegible]	[illegible]	18.9	18.9	18.9	18.9	18.9	18.9
Runoff	Q_{TOTAL}	lpm	6.4	7.2	6.1	6.1	6.4	5.3	16.6	14.0	13.2	13.6	10.6	9.5
Runoff %		%	34	38	32	31	34	27	88	74	71	71	56	51

Ideal Carryover

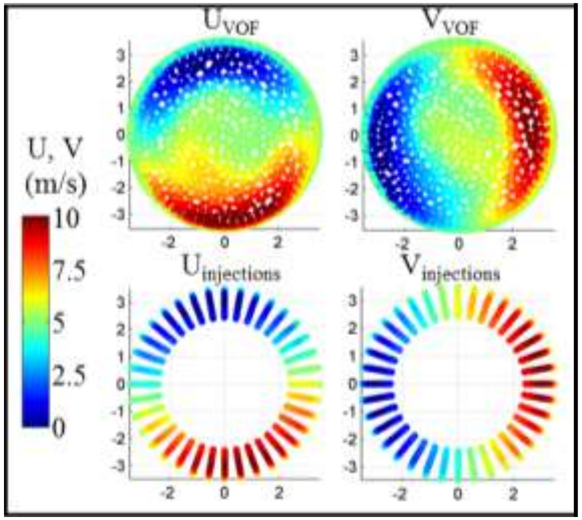
CFD Setup

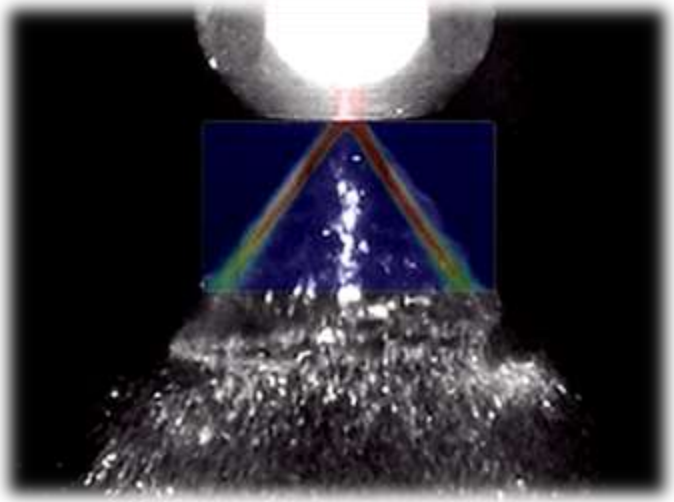
- **Boundary Conditions**
  - Inlet: Constant Velocity
  - Outlet: Constant Pressure
  - Wall: Rigid, no slip, adiabatic
- **Model Selection**
  - k-ε Realizable Turbulence Model
  - DPM for LaGrangian tracking of water droplets
  - Species Transport
- **Mesh Considerations**
  - Dense near injection/orifice, course elsewhere
    - Approx. 2M cells

Nozzle Data Input

Based on empirical data acquired in laboratory.

- Specific functions are employed to customize nozzle's spray characteristics that cannot be matched with FLUENT's standard injection library
- Customized "Injection Creation" files are coded where large number of spray nozzles are used and improve accuracy of the simulations

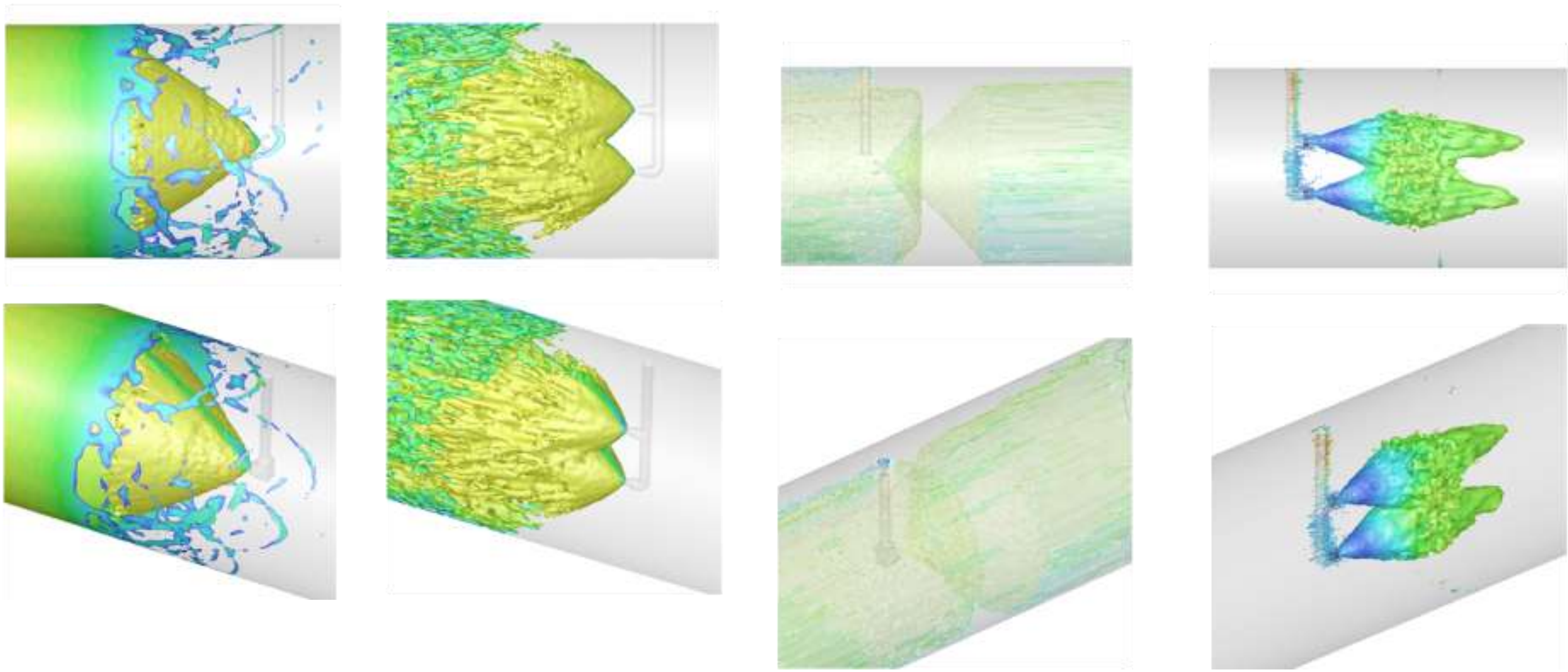




Spray Visualization – DPM Conc.

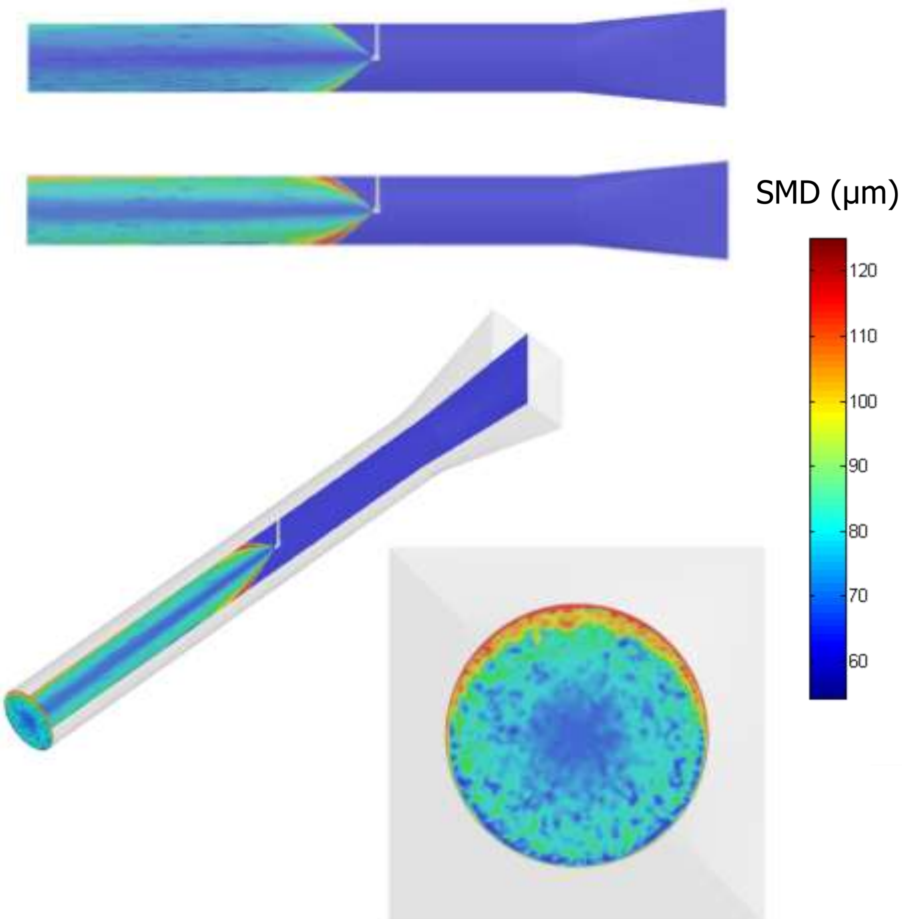
Gas flow

Co-Current (DPM Conc. Results)		Counter-Current (DPM Conc. Results)	
Hollow cone (3/8BX-15) - 30 m/s	Dual Full cone (1/4HH-6.5) - 30 m/s	Hollow cone (3/8BX-15) - 30 m/s	Dual Full cone (1/4HH-6.5) - 30 m/s

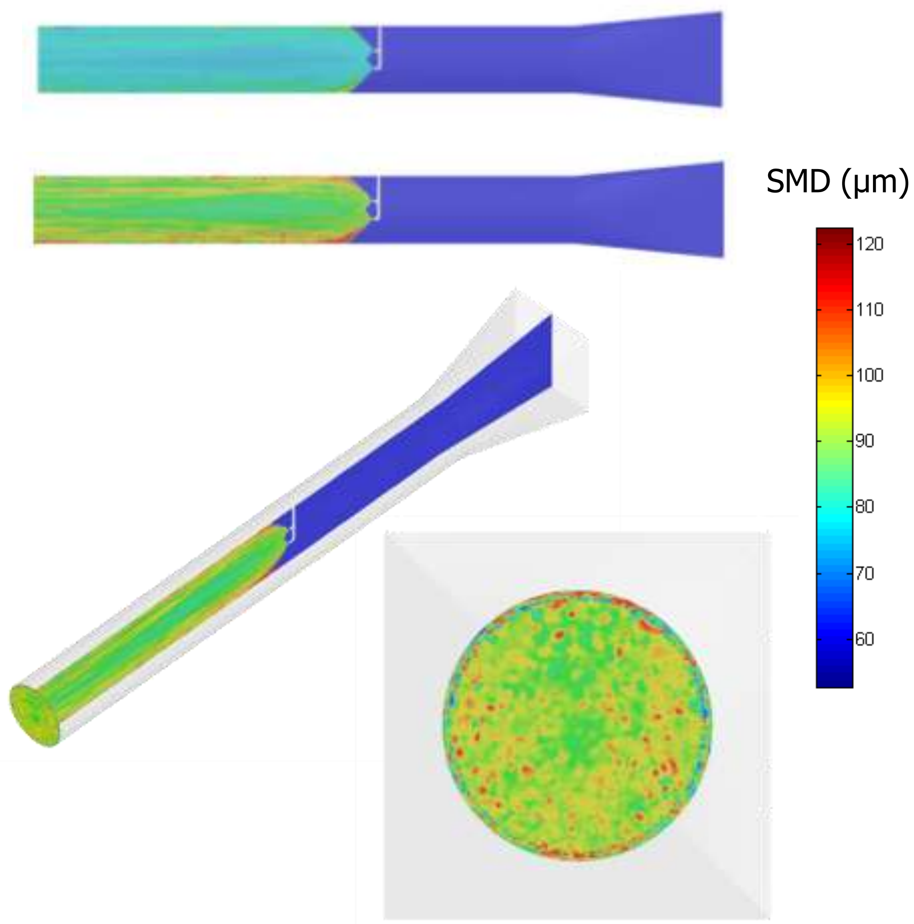


Drop Size (20m/s, co-current)

Hollow cone
(3/8BX-15) - 20 m/s

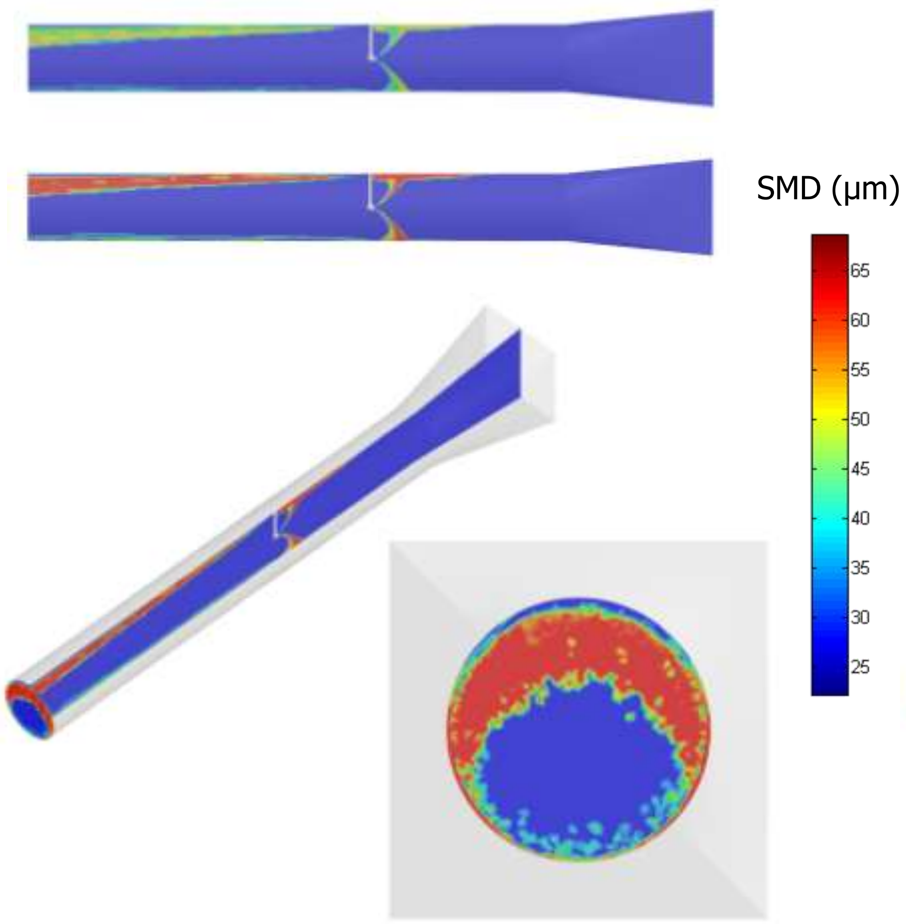


Dual Full cone
(1/4HH-6.5) - 20 m/s

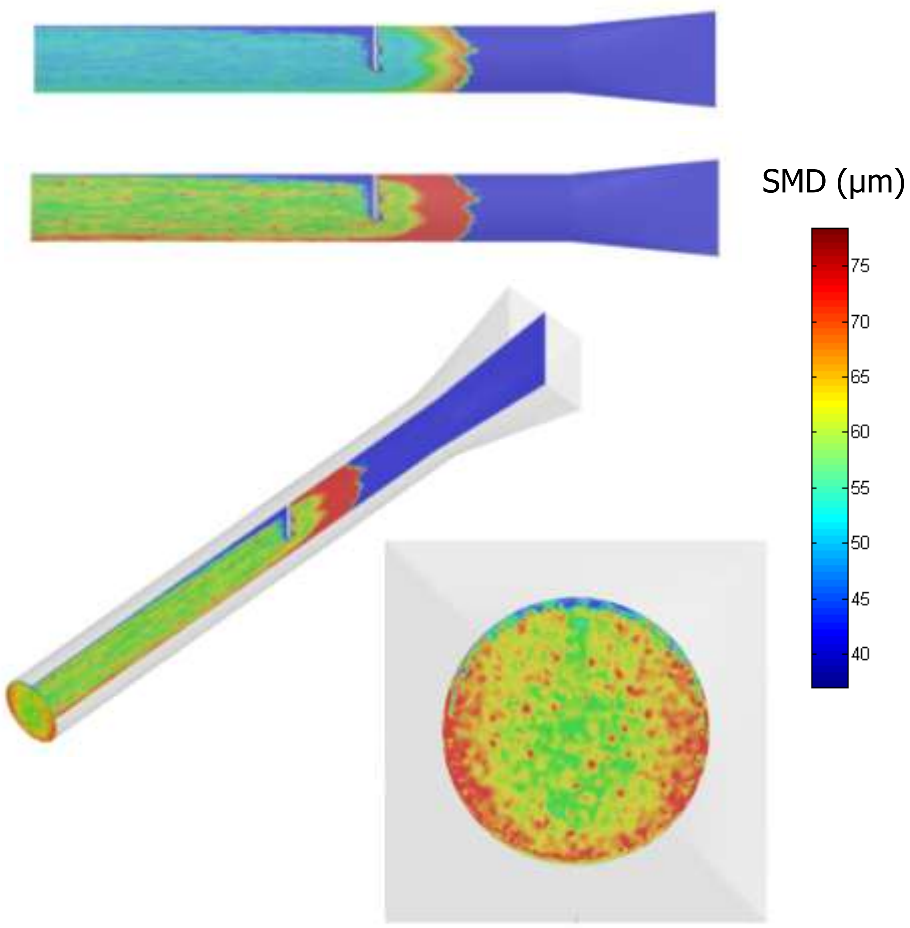


Drop Size (20m/s, counter-current)

Hollow cone
(3/8BX-15) - 20 m/s

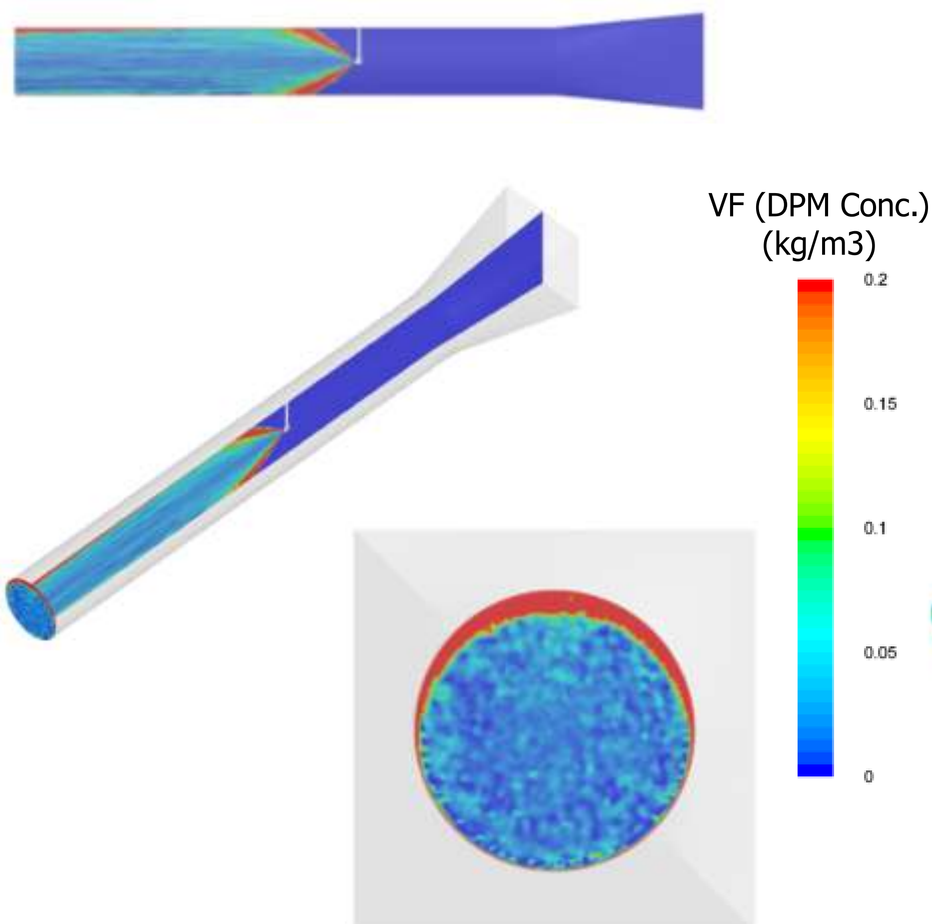


Dual Full cone
(1/4HH-6.5) - 20 m/s

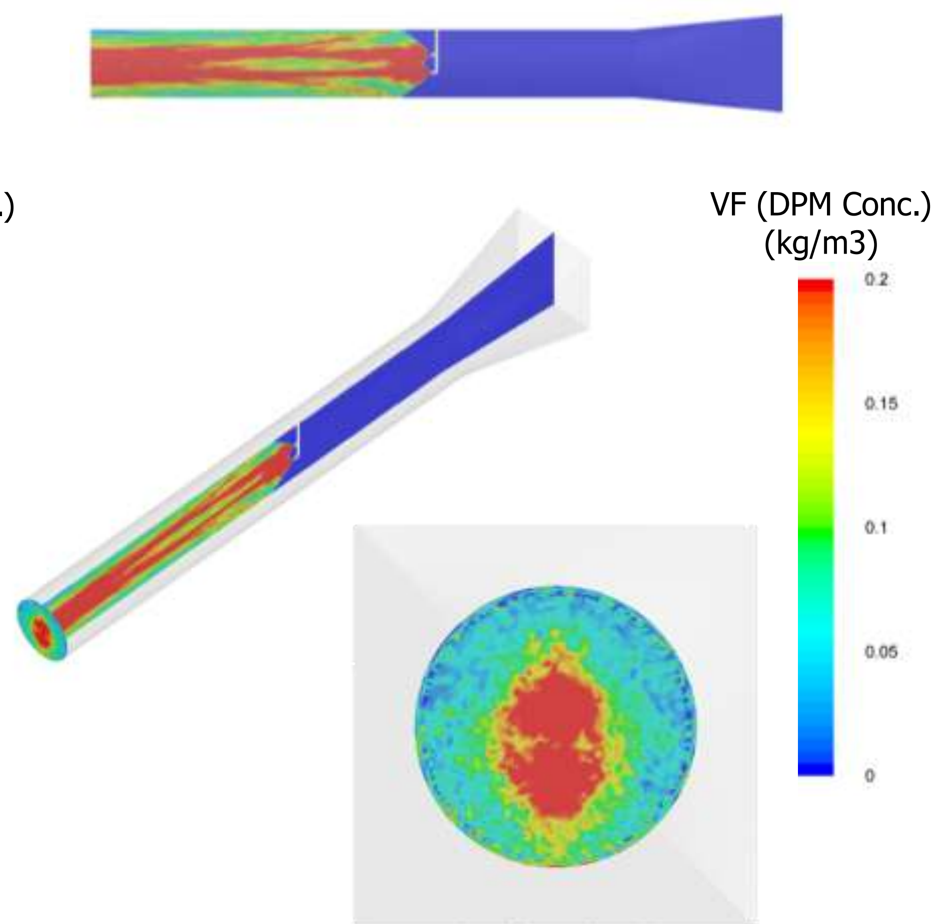


Spray Distribution (20m/s, Co-current)

Hollow cone
(3/8BX-15) - 20 m/s

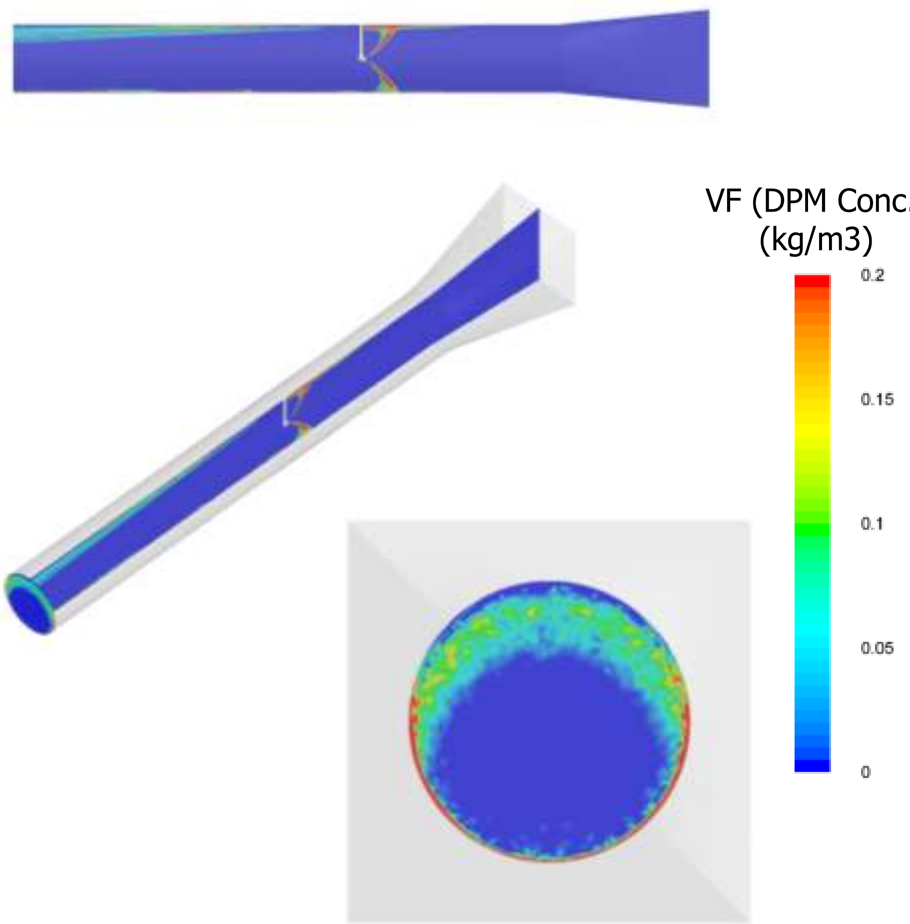


Dual Full cone
(1/4HH-6.5) - 20 m/s

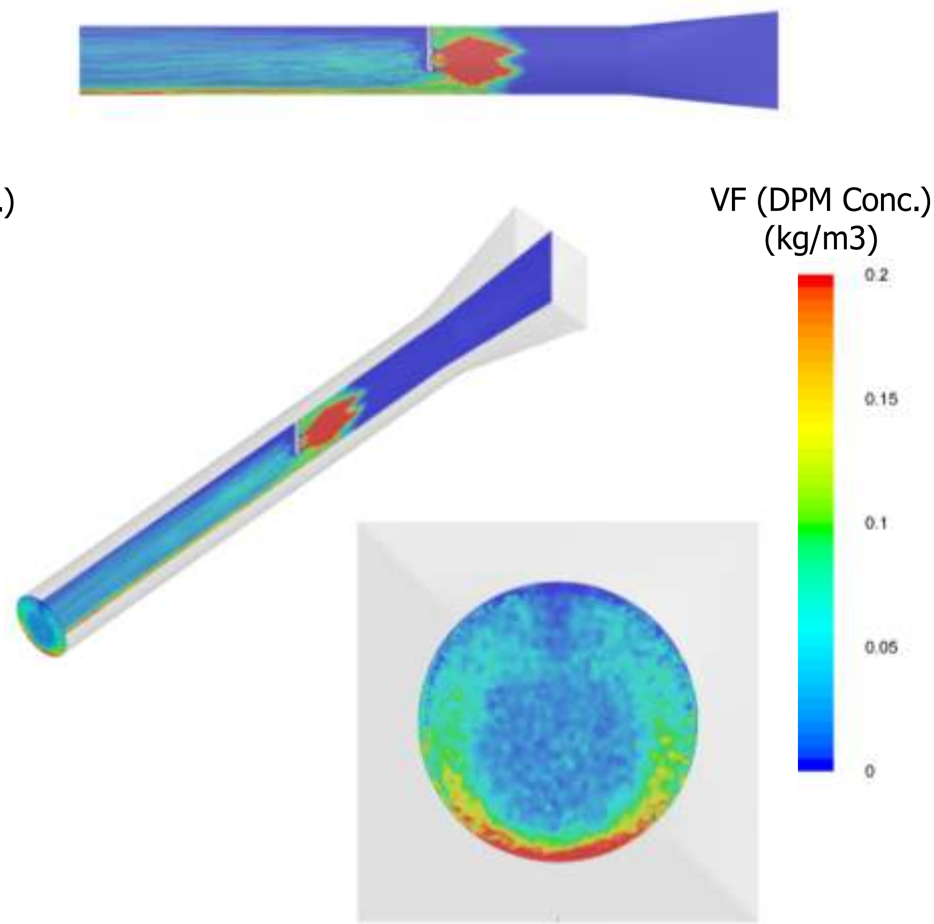


Spray Distribution (20m/s, Counter-current)

Hollow cone
(3/8BX-15) - 20 m/s



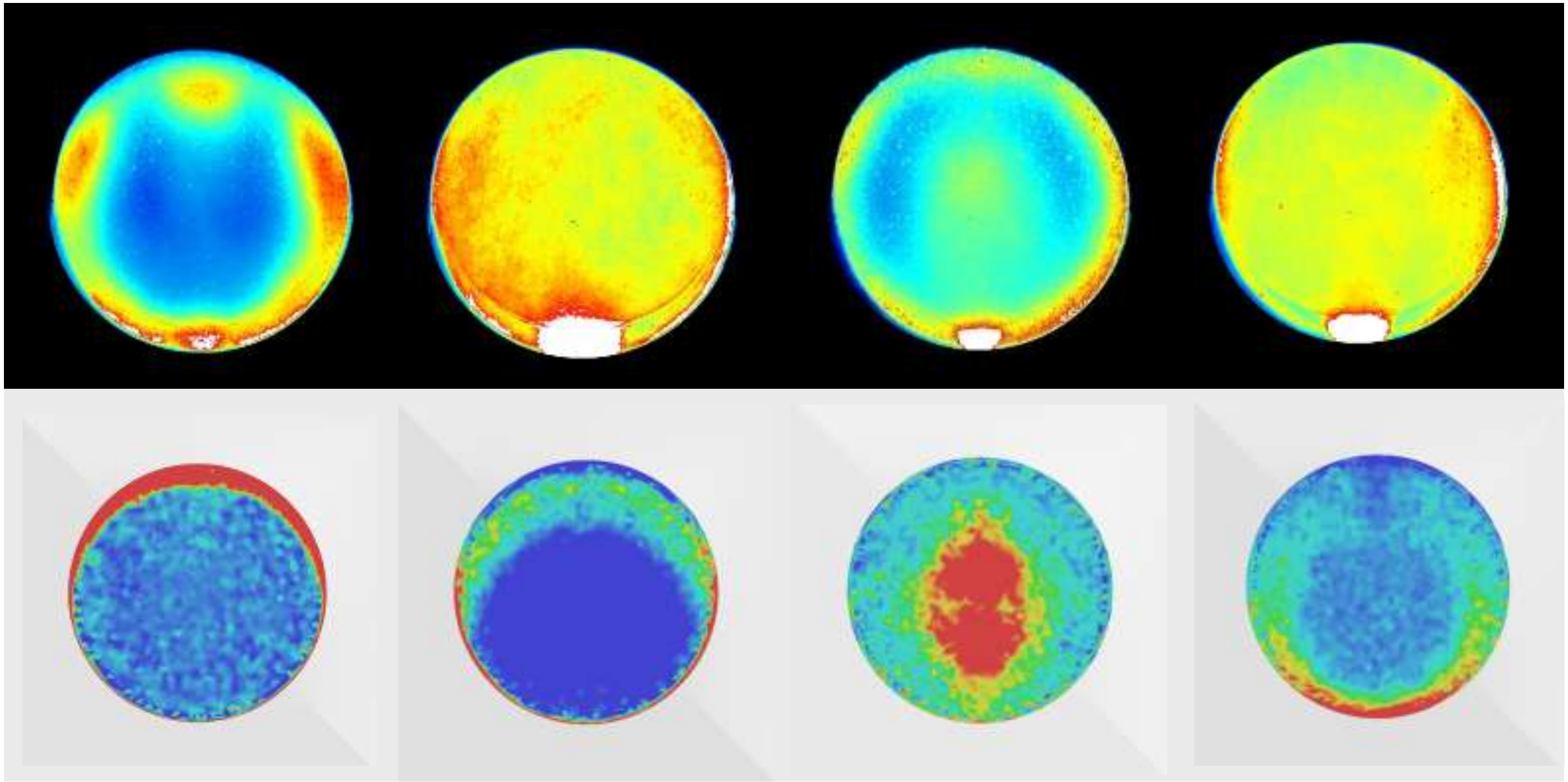
Dual Full cone
(1/4HH-6.5) - 20 m/s



Empirical Vs. Simulation

Distribution Comparison

Hollow cone (3/8BX-15) - 20 m/s	Dual Full cone (1/4HH-6.5) - 20 m/s

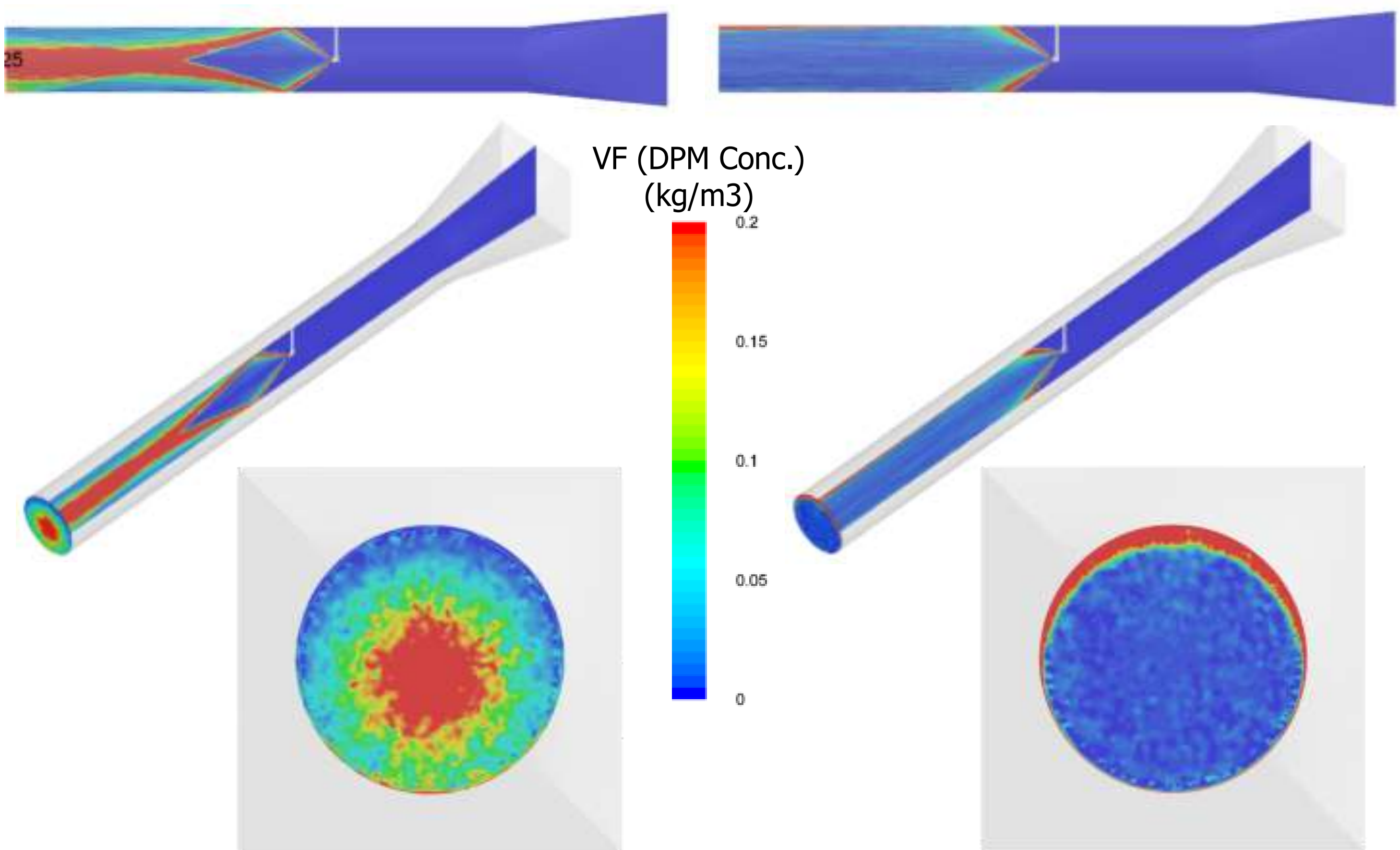


Wall Boundary Conditions

Hollow Cone (3/8BX-15) Co-Current

Wall-film BC at duct walls - 20 m/s

Wall-jet BC at duct walls - 20 m/s



Conclusions[1]

Hollow cone

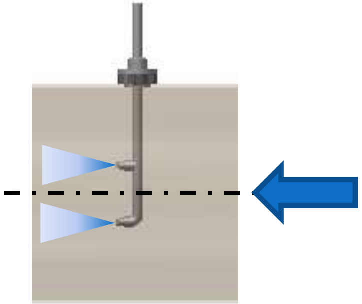
Less uniformity / Dispersion
Quick attachment to wall
Dependent on secondary shear
Large Free Passage (No clogging)

Dual Full cone

Best Uniformity /Dispersion
Greater distance to wall attachment
Longer adherence to wall
Smallest Free Passage

Conclusions²

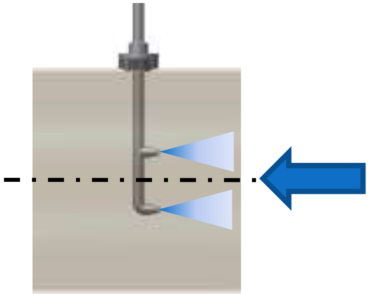
Co-current



Co-Current Flow Conditions

- Less uniformity / Dispersion
- Greater entrainment of full volume of spray
- Less evidence of secondary breakup appears

Counter-current



Counter-Current Flow Conditions

- Better uniformity / Dispersion
- Quick wall attachment
- Entrainment/small particles, large amount of run-off

Next Steps

- *Secondary breakup estimation with & without transient CFD*
  - Additional measurement locations (from injector)
- Wall interference studies
- User feedback
  - Corrosion and de-salting effectiveness

Thank You