Business from technology

Experimental characterization and CFD modelling of high pressure water mist sprays

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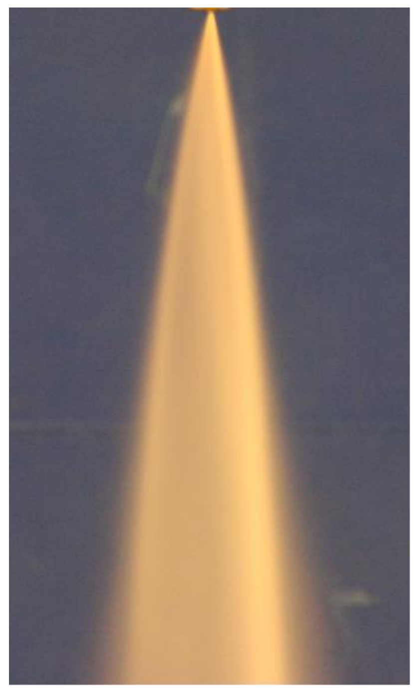
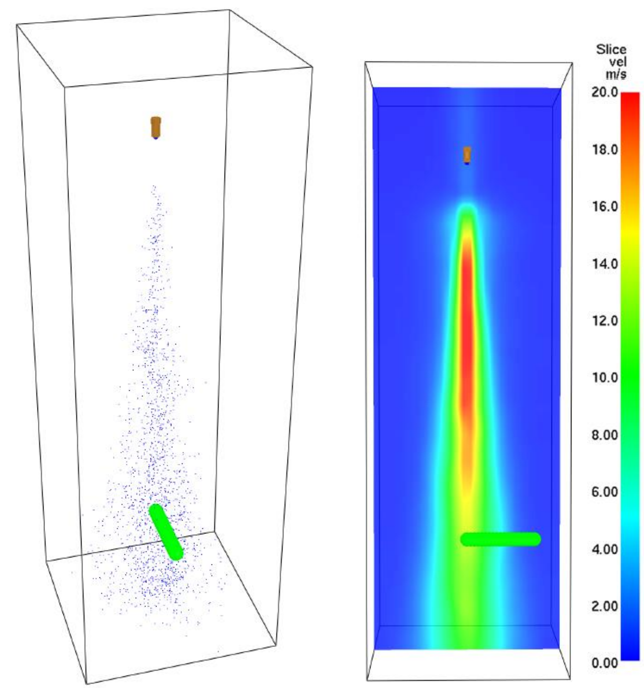
Introduction

- Goal: creating a physically correct model of a high pressure water mist spray with Fire Dynamics Simulator
- Physically correct:
  - Drop size profile
  - Drop velocity profile
  - Mist flux profile
  - Air entrainment
  - Water distribution

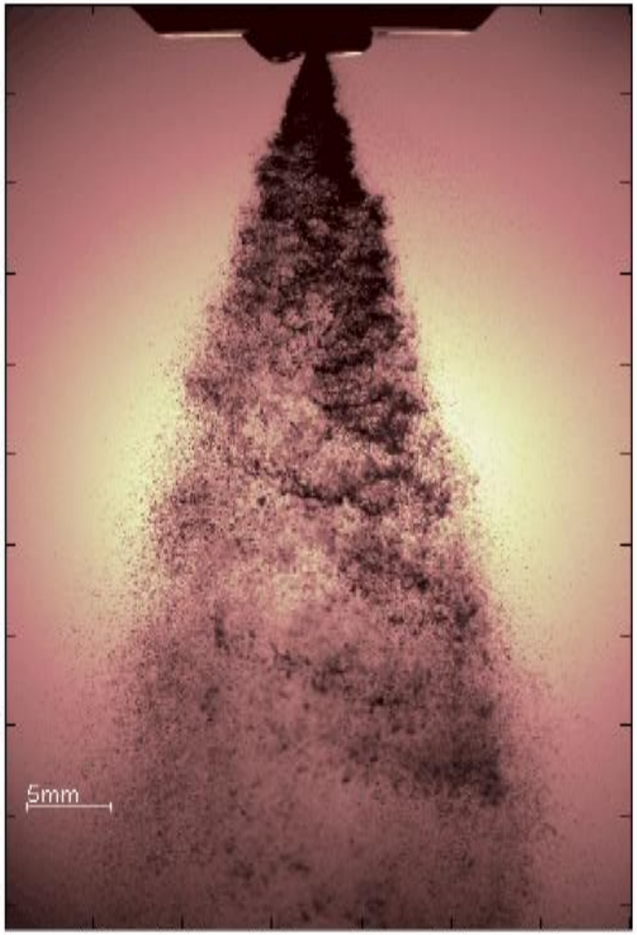




(a) (b)

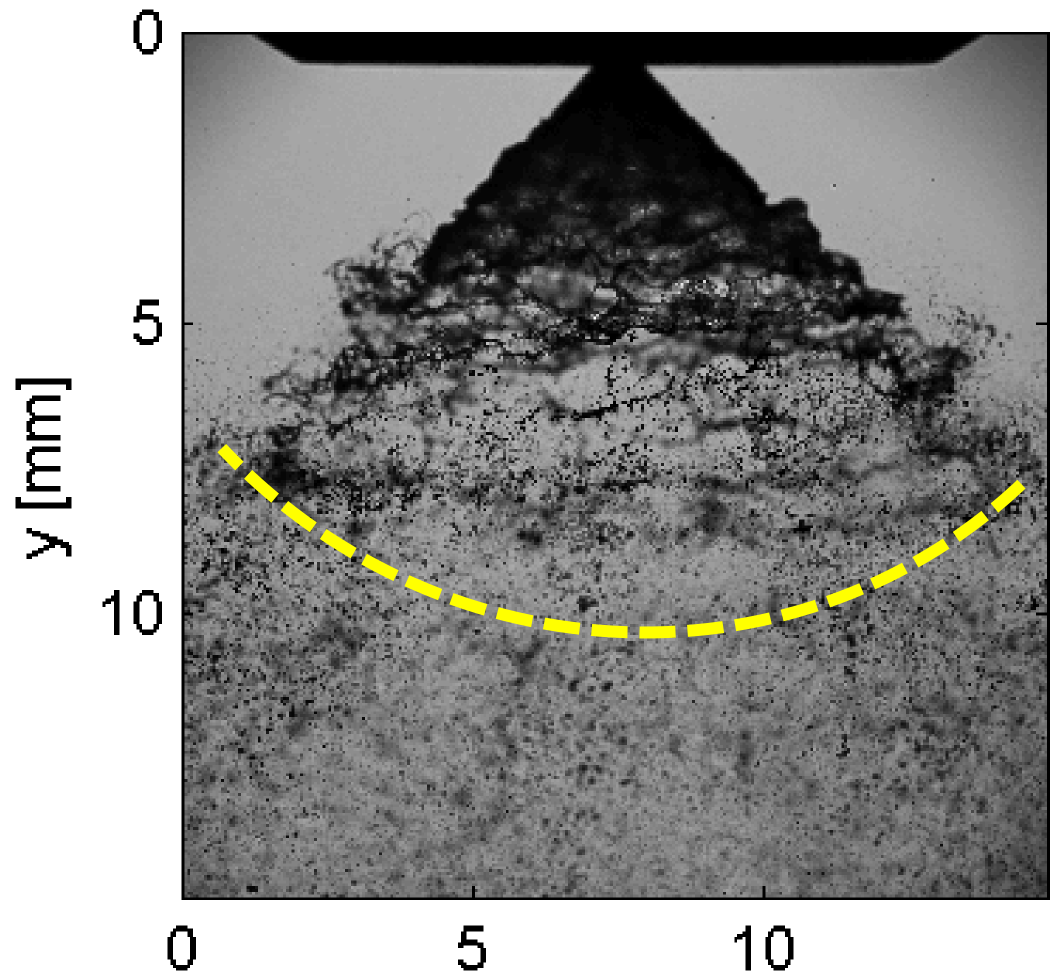
FDS model parameters for nozzles

```
&DEVC XYZ=0.0, 0.0, 2.5
      QUANTITY='TIME'
      SETPOINT=0.0
      PROP_ID=‘MY NOZZLE' /

&PROP ID=‘MY NOZZLE'
      OFFSET=0.05
      PARTICLES_PER_SECOND=5000
      PART_ID='WATER DROPLETS'
      OPERATING_PRESSURE= 70.0000
      K_FACTOR= 0.35
      DROPLET_VELOCITY=110.0
      SPRAY_ANGLE=0.0, 10.0 /

&SPEC ID='WATER VAPOR' /

&PART ID='WATER DROPLETS'
      SPEC_ID='WATER VAPOR‘
      DIAMETER=80.
      GAMMA_D=2.4 /
```



OFFSET

- No model for atomization in FDS
- Droplets are inserted in the simulation at a distance (offset) from orifice where atomization is complete
- OFFSET=0 is possible but may sometimes be numerically awkward



VELOCITY

- The exit velocity of a liquid jet from the discharge orifice may be estimated from Bernoulli's law as

$$v = C\sqrt{\frac{2p}{\rho}}$$

  - Pressure in Pascals (1 bar = 10^5 Pa)
  - For water, ρ=1000 kg/m^3
  - Discharge coefficient C depends on nozzle geometry and liquid Reynolds number (0.6 – 1)
- Alternatively it is possible to define orifice diameter and flow rate from which the velocity is computed by FDS (assuming C=1)

DIAMETER

- Atomization leads to a spectrum of drop sizes
- FDS describes the drop size spectrum as a combination of log-normal and Rosin-Rammler distributions
- The diameter given as input is $D_{V,0.5}$, the Volume Median Diameter of the distribution
- FDS6 offers the user an option to input an arbitrary size distribution

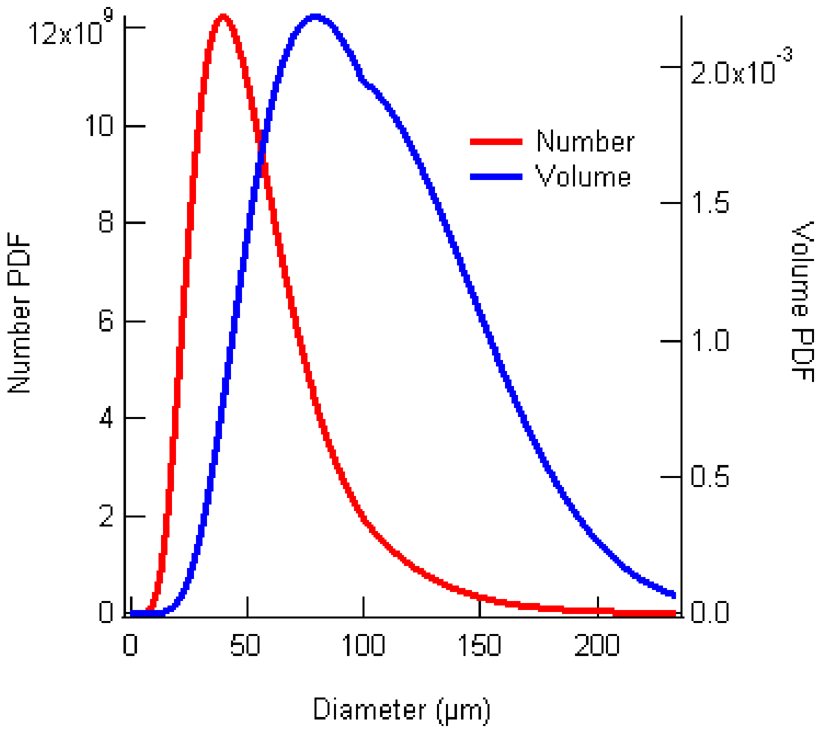
$$F(d) = \begin{cases} \frac{1}{\sqrt{2\pi}} \int_0^d \frac{1}{\sigma d'} e^{-\frac{[\ln(d'/d_m)]^2}{2\sigma^2}} \, \mathrm{d}d' & (d \leq d_m) \\ 1 - e^{-0.693\left(\frac{d}{d_m}\right)^\gamma} & (d_m < d) \end{cases}$$

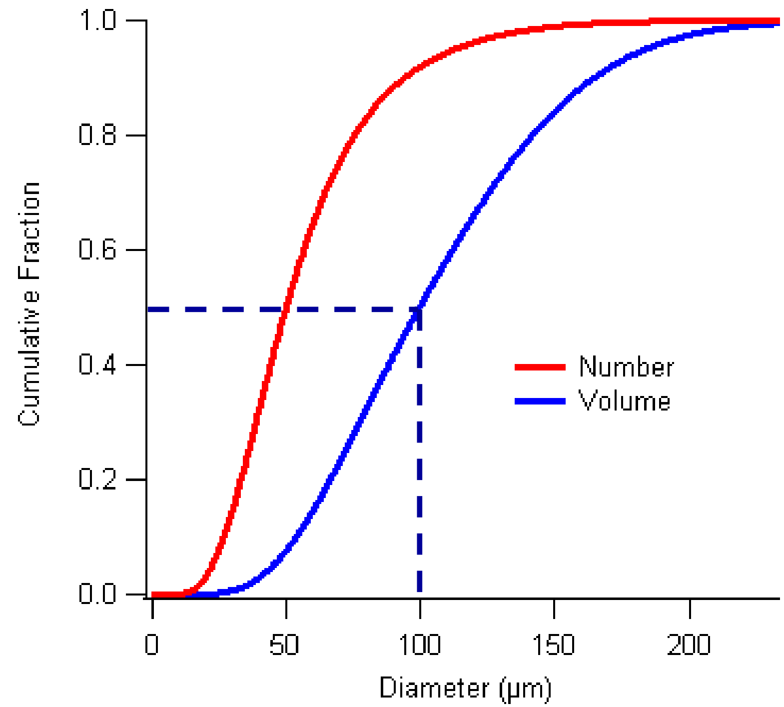
$$f(d) = \frac{F'(d)}{d^3} \bigg/ \int_0^\infty \frac{F'(d')}{d'^3} \, \mathrm{d}d' \quad ; \quad F' \equiv \frac{\mathrm{d}F}{\mathrm{d}d}$$

F(d) is the fraction of liquid volume in droplets smaller than d
f(d) is the fraction of droplets smaller than d

DIAMETER

- Example: $D_{V,0.5}$=100 µm, γ=2.4

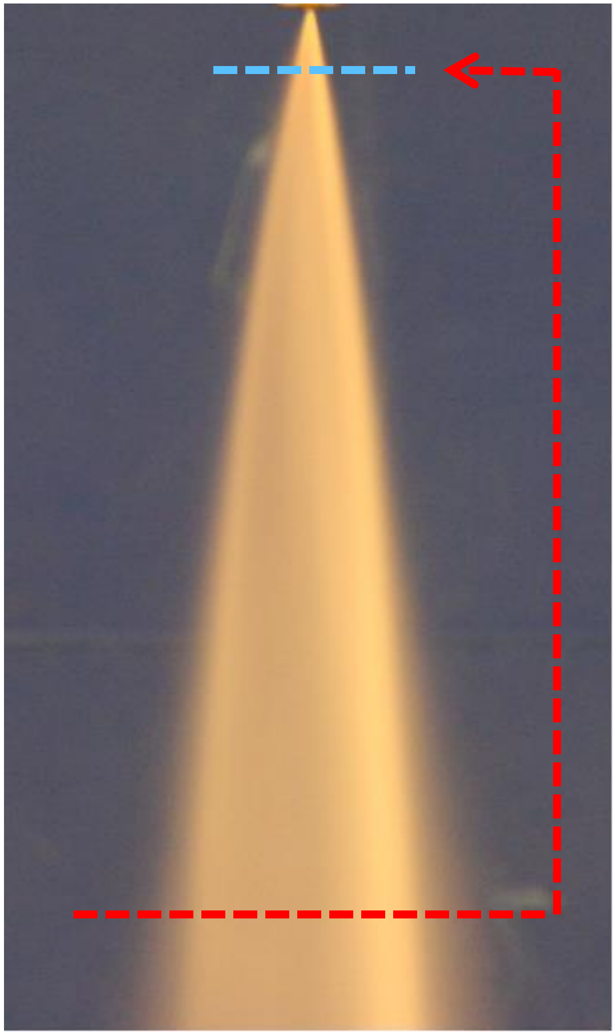




How to obtain the numbers?

Method 1

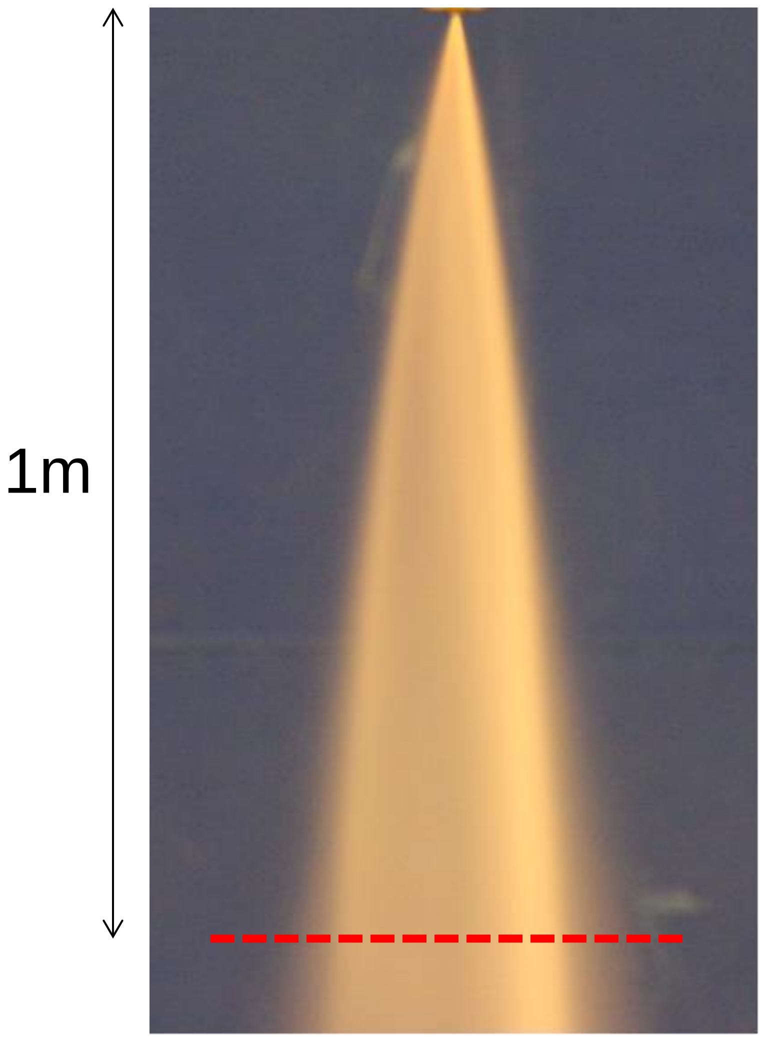
- Measurements close to discharge orifice (~0.1m)
  - Diameter
  - Velocity
  - Flux
- Use as inputs at measurement plane (offset distance)
- Problems:
  - Dense spray
  - Incomplete atomization
  - Verification

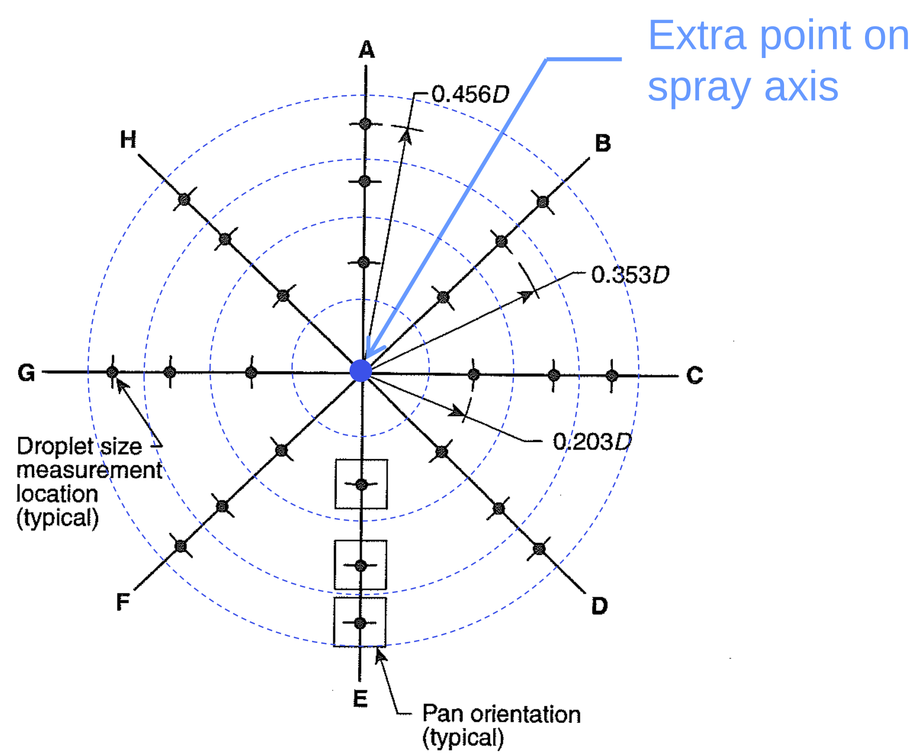


Method 2

- Measurements far away from discharge orifice (~1m)
  - Diameter
  - Velocity
  - Flux
- Use diameter as input at offset distance
- Verify results at measuring distance
- Problem:
  - Velocity (momentum conservation)

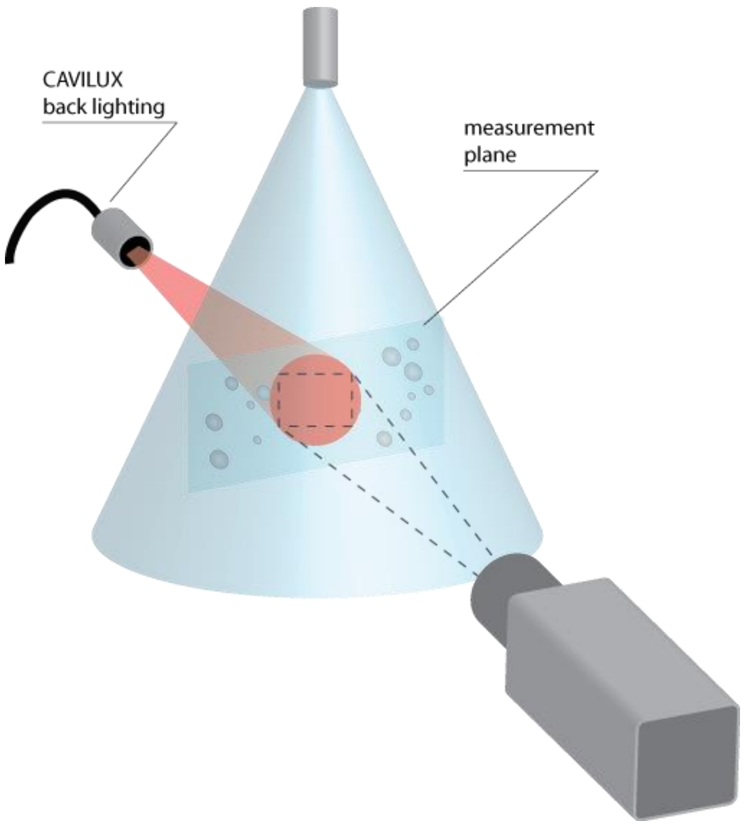
Nozzle characterization with modified NFPA750





$$GRV_j = \frac{\sum_i (R_{i,j} \times A_i \times V_i)}{\sum_i (A_i \times V_i)}$$

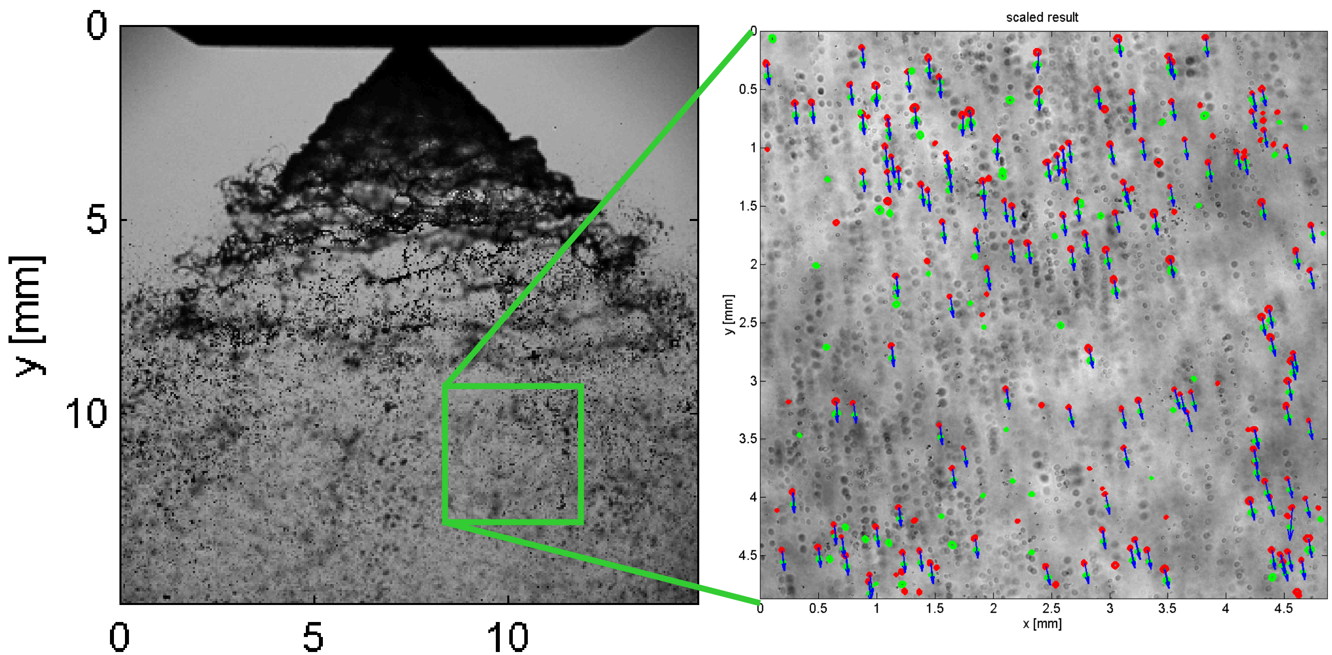
Digital Imaging (Shadowgraphy)

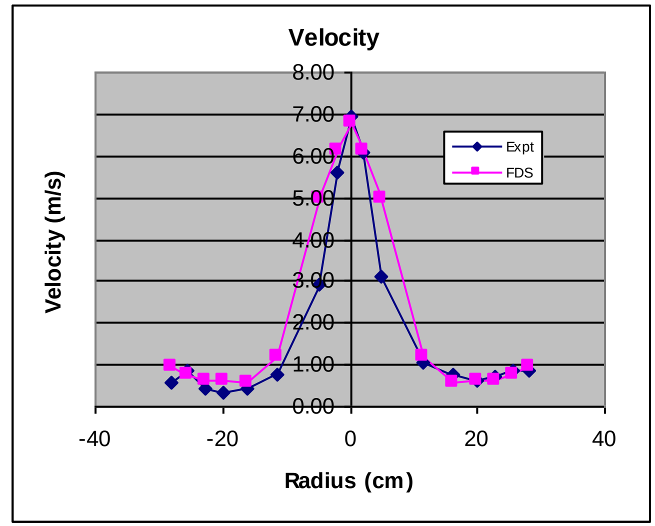


Camera	
resolution	2009: 2048 x 2048 (JAI), 2010: 1600 x 1200 (Lynx)
Camera optics	
objective	Nikon 200 mm macro + 2x converter (=400 mm)
Laser	Cavilux Smart
type	Diode laser
max. power	560 W / 2.8 mJ per pulse
wavelength	690 nm

- Measurement volume 12mm x 12mm x 3 mm
- Smallest detectable drop diameter about 10 µm

Digital Imaging (Shadowgraphy)





- Diameter and concentration directly from pattern recognition
- Velocity by particle tracking from two images taken with $\Delta t=5\mu s$

High-pressure micronozzles

- Three high-pressure micronozzles characterized experimentally and modelled with FDS (svn 10155)

	A	B	C
Type	Full-cone	Full-cone	Full-cone
K-factor (l/min/bar$^{1/2}$)	0.2	0.43	0.77
Pressure (bar)	?	?	?
Velocity (m/s)	?	?	?
Cone angle (deg)	?	?	?
$D_{v,0.5}$ (µm)	?	?	?
γ	?	?	?
Offset (m)	?	?	?
Particles per second	?	?	?

```
&DEVC XYZ=0.0, 0.0, 2.5
      QUANTITY='TIME'
      SETPOINT=0.0
      PROP_ID='MY NOZZLE' /

&PROP ID='MY NOZZLE'
      OFFSET=0.05
      PARTICLES_PER_SECOND=5000
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&PART ID='WATER DROPLETS'
      SPEC_ID='WATER VAPOR'
      DIAMETER=80.
      GAMMA_D=2.4 /
```
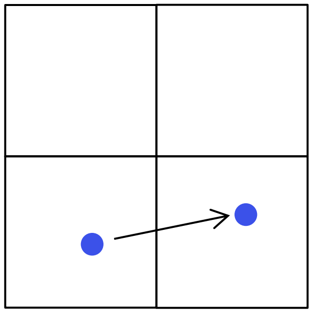

Model parameters for micronozzles

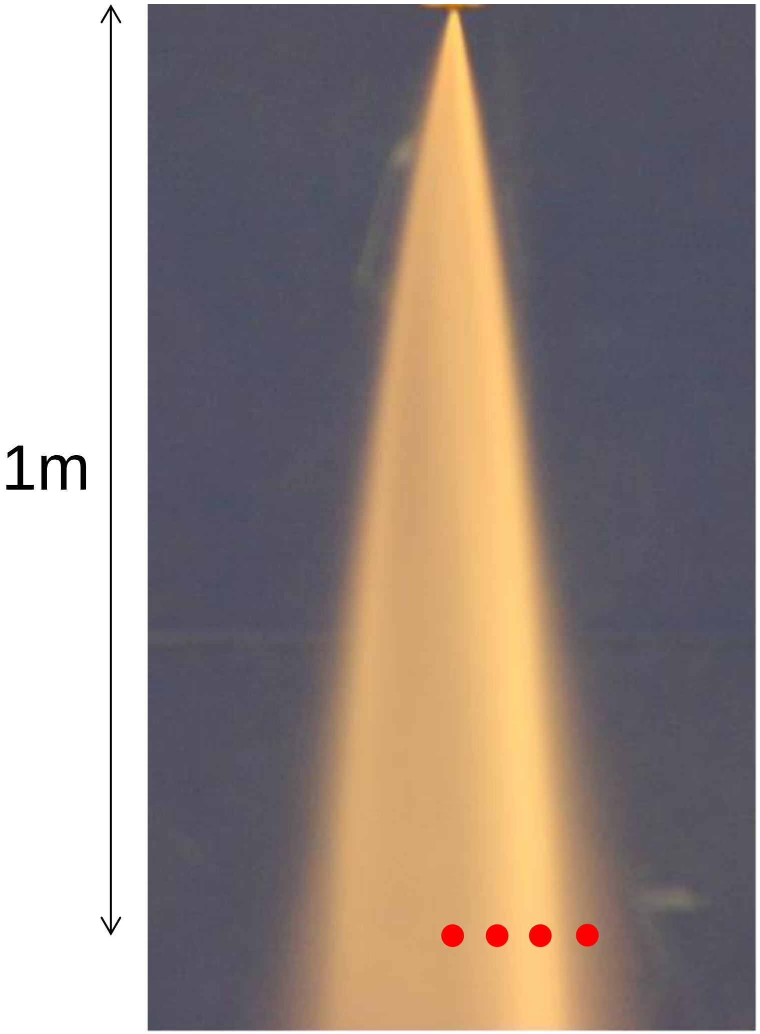
	A	B	C	
Type	Full-cone	Full-cone	Full-cone	
K-factor (l/min/bar$^{1/2}$)	0.2	0.43	0.77	
Pressure (bar)	70	70	70	User decision
Velocity (m/s)	112	112	112	From Bernoulli's law (C=0.95)
Cone angle (deg)	10	12	14	From photographs
$D_{v,0.5}$ (µm)	84	79	116	From experimental GRV
γ	2.9	2.26	1.98	From experimental GRV
Offset (m)	0.1			Trial & error
Particles per second	200000			Trial & error

Other modeling considerations

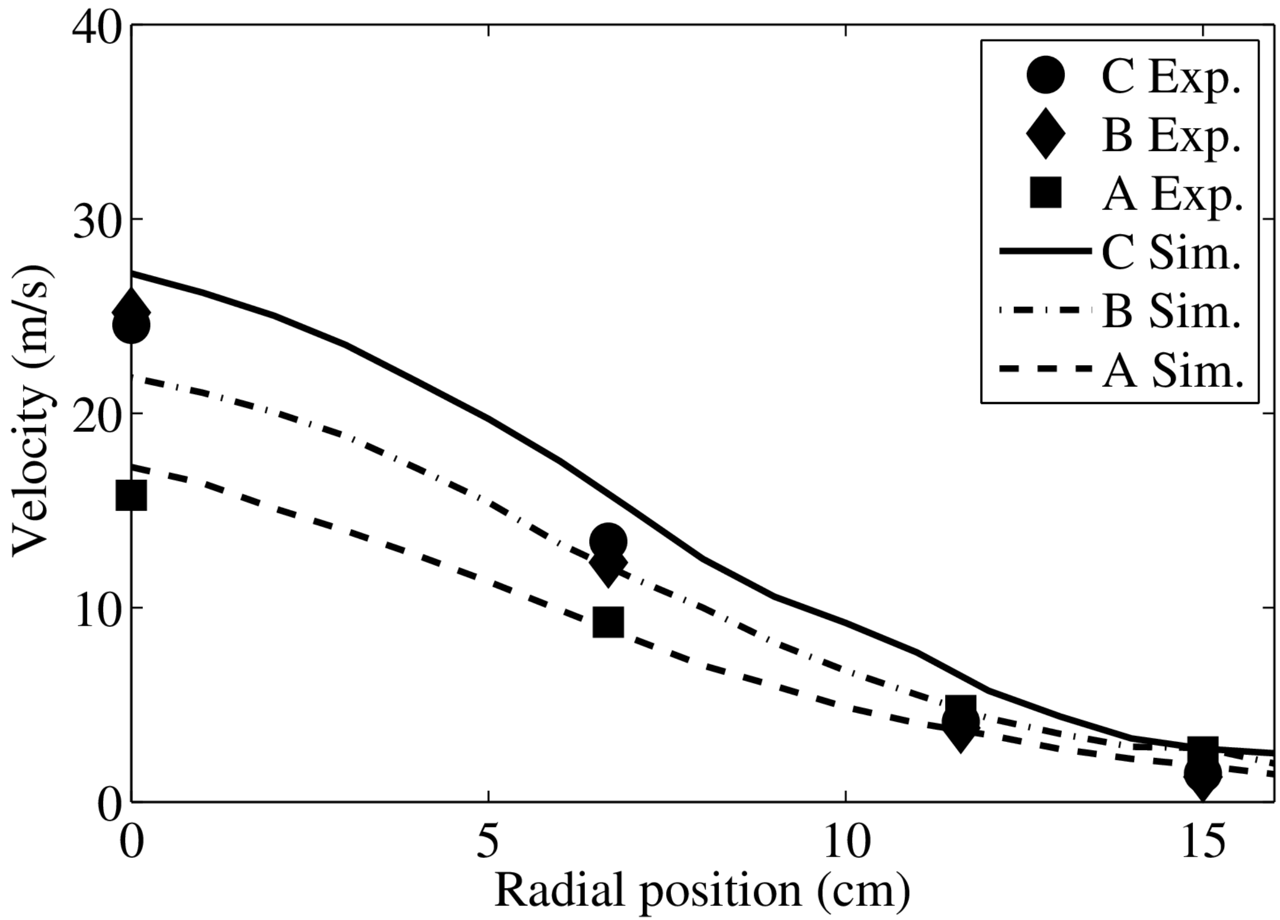
- Discretization interval (grid resolution)
- Particle CFL parameter
- Turbulence model
  - Deardorff (FDS 6 default)
  - Vreman
  - Constant Smagorinsky (FDS 5 default)
  - Dynamic Smagorinsky



Micronozzles: velocity

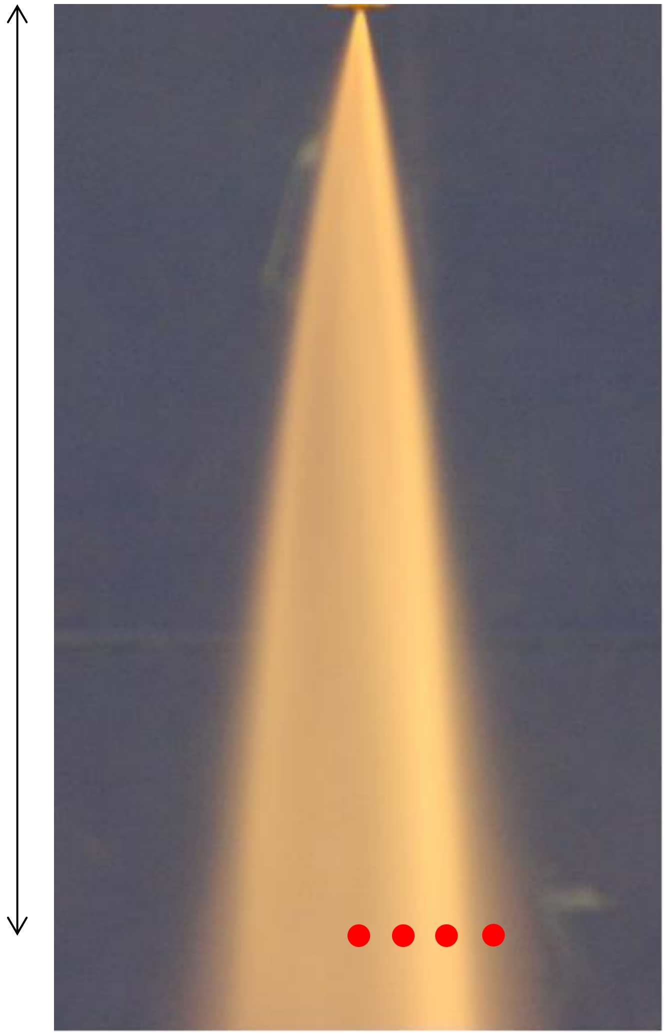


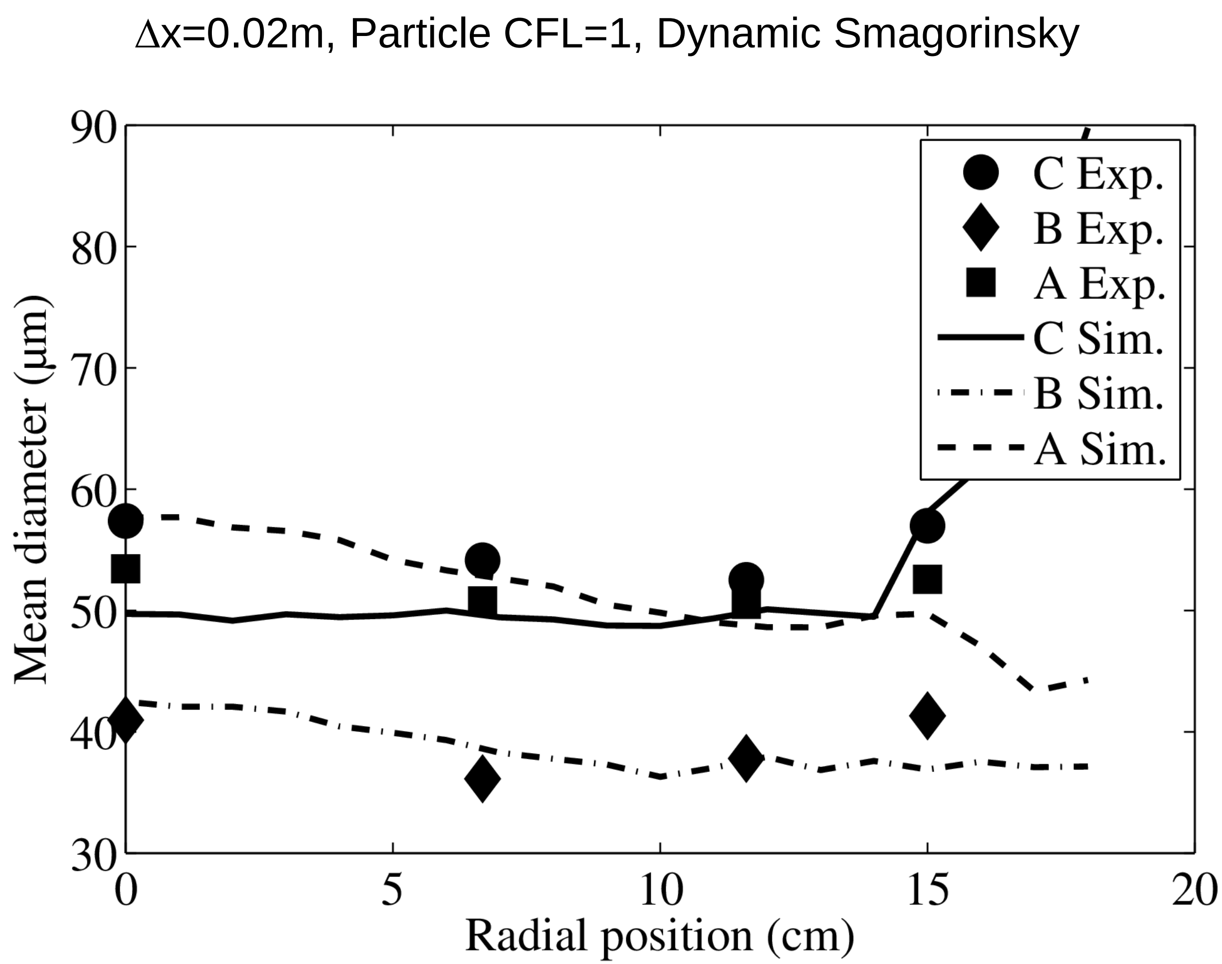
Δx=0.02m, Particle CFL=1, Dynamic Smagorinsky



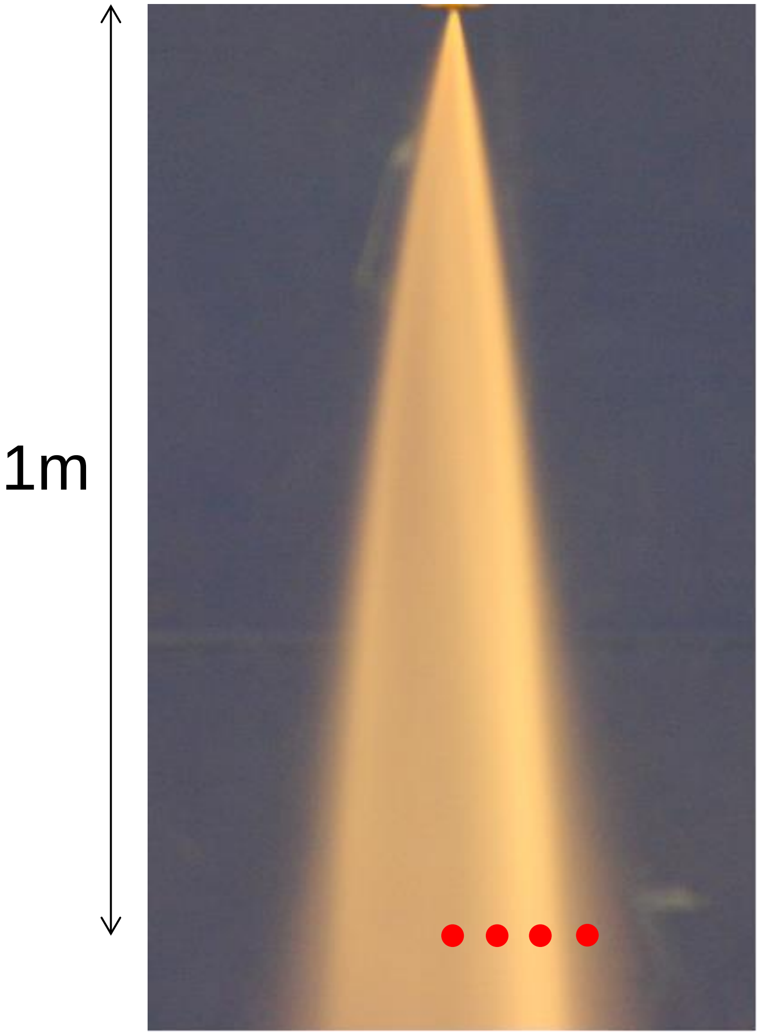
Micronozzles: mean diameter

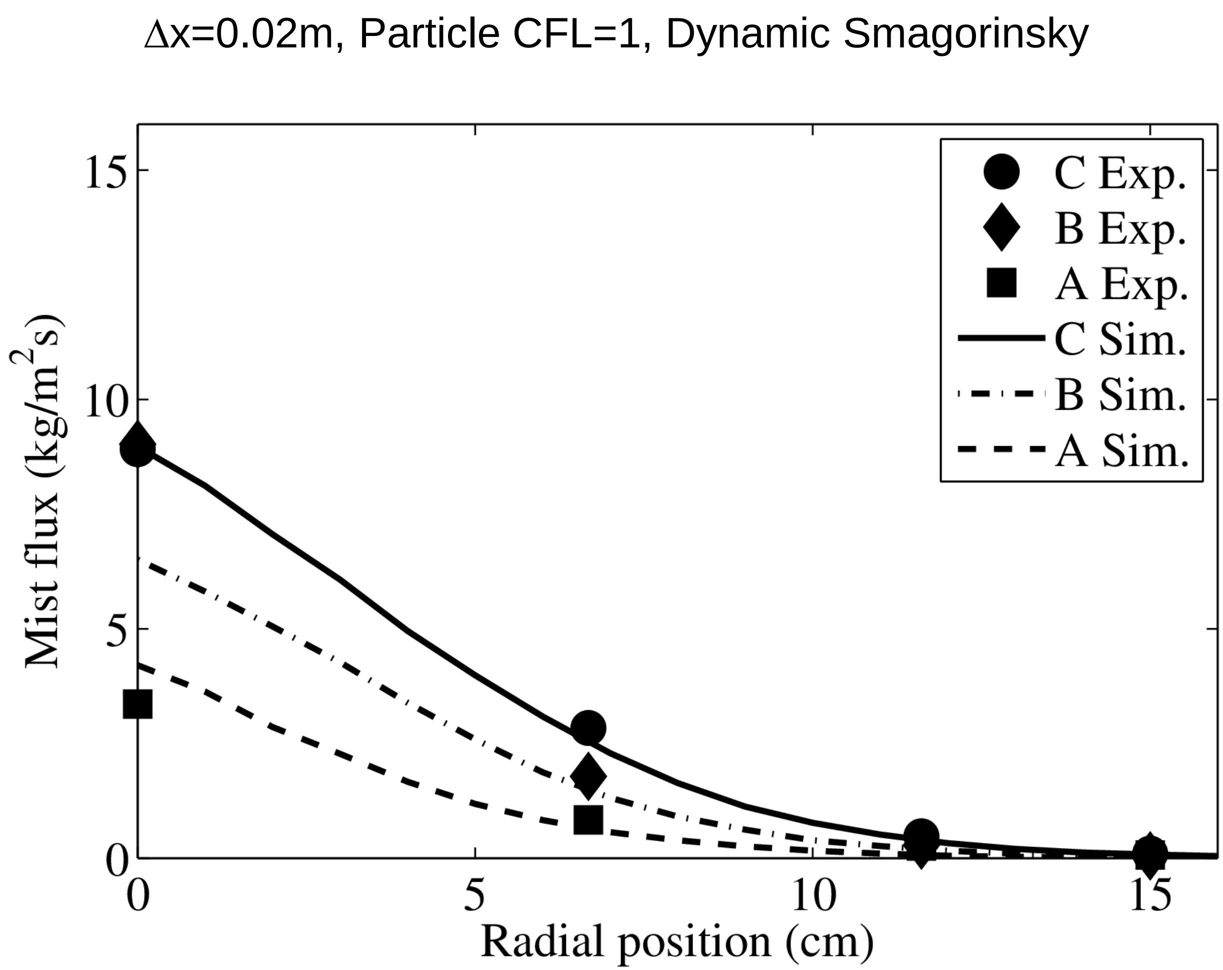
1m



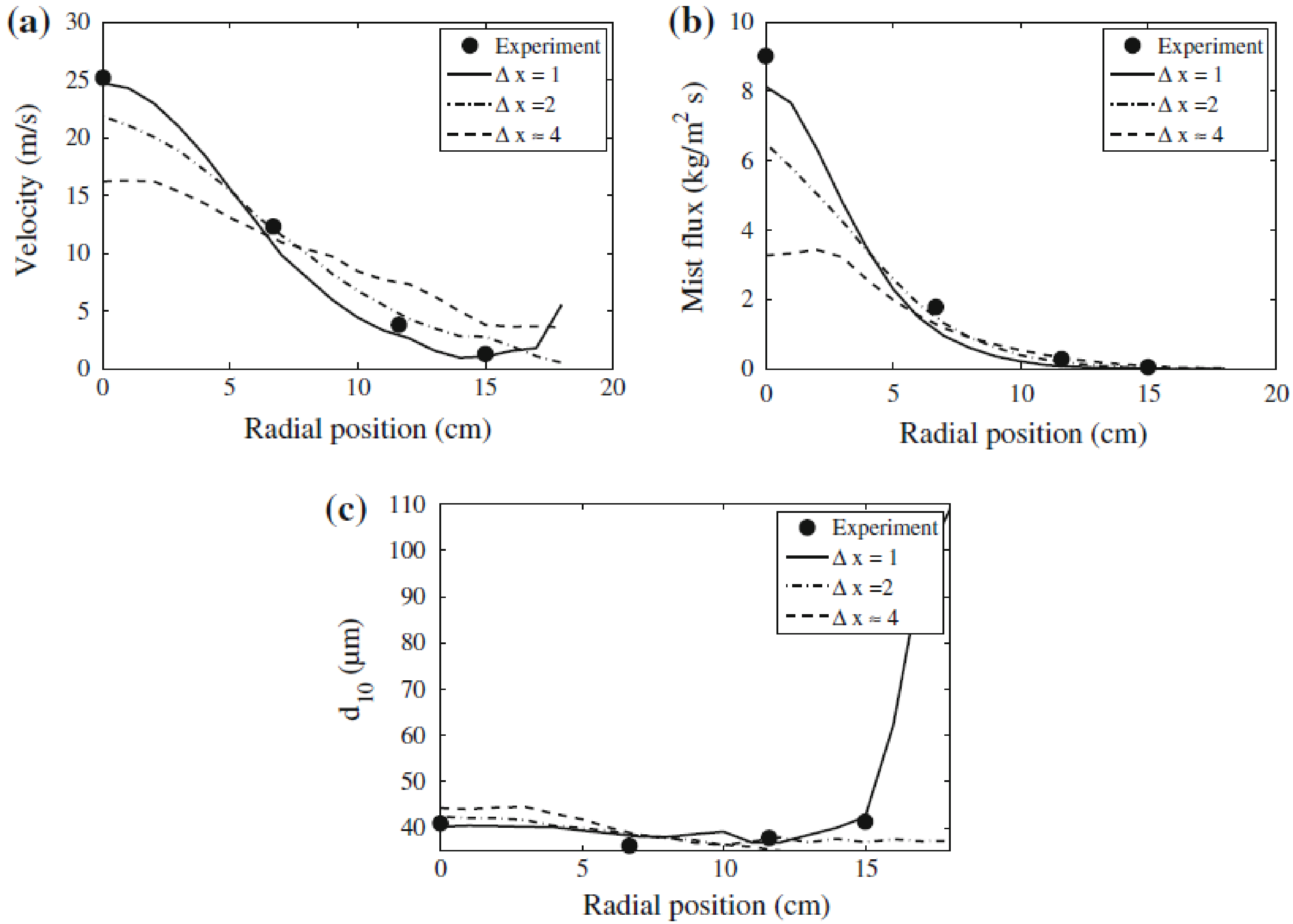


Micronozzles: mist flux



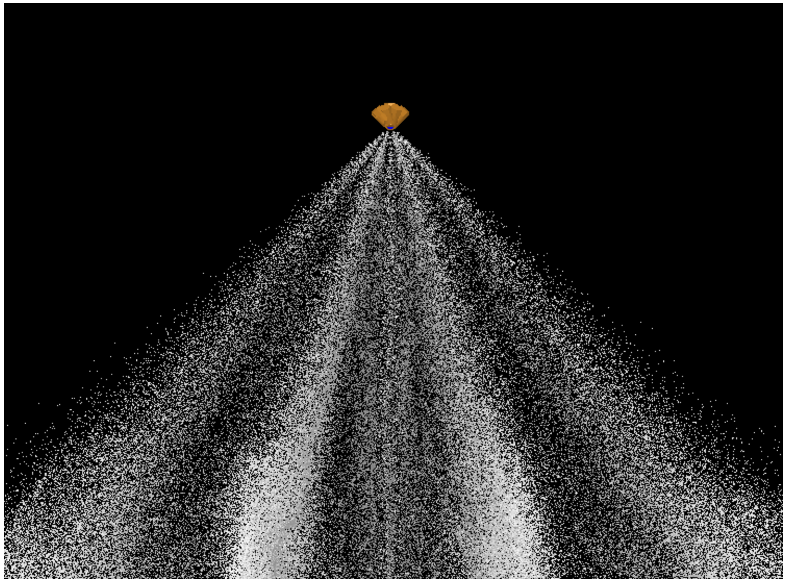


Grid sensitivity



FDS: constructing a multi-orifice spray head

- In FDS, a multi-orifice spray head is constructed analogously to a real spray head: by placing several micronozzles to the same physical location but with different orientations



```
&DEVC XYZ=0.0,0.0,5.000 PROP_ID=‘NZLE' ORIENTATION= 0.7071, 0.0000, -0.7071 QUANTITY='TIME' SETPOINT=0.0 ID='45_1' /
&DEVC XYZ=0.0,0.0,5.000 PROP_ID=‘NZLE' ORIENTATION= 0.5000, 0.5000, -0.7071 QUANTITY='TIME' SETPOINT=0.0 ID='45_2' /
…
…
```

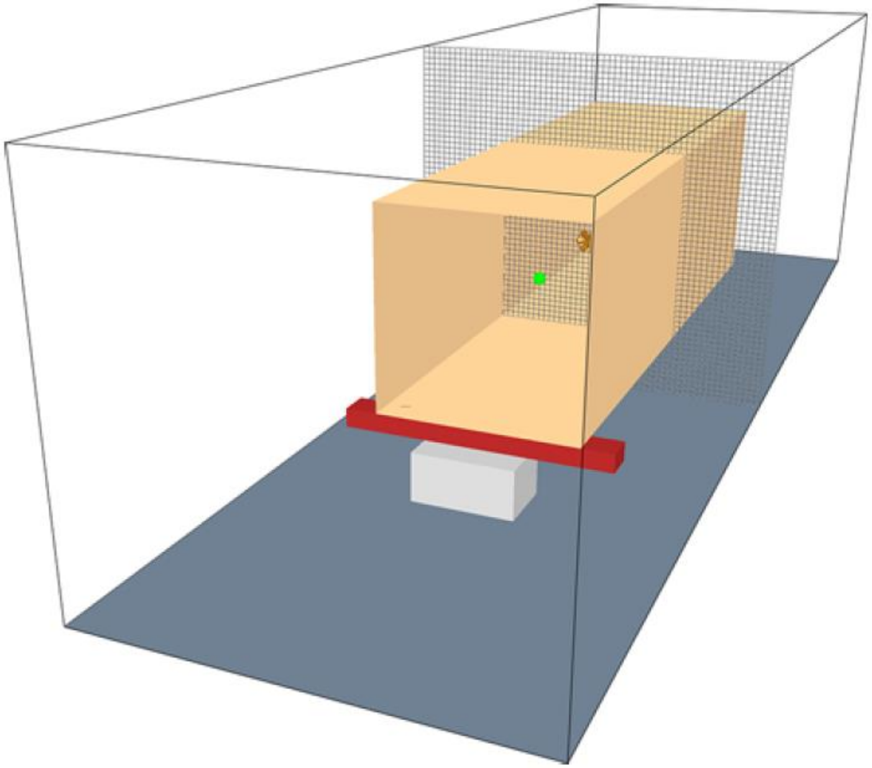
Multi-orifice SPH's

- Spray heads constructed of micronozzles A, B, and C

	SH1	SH2	SH3	SH4	SH5
Center nozzle	A	C	B	B	B
Perimeter nozzle	A	B	A	B	B
Number of perimeter nozzles	6	6	8	8	8
Perimeter angle (°)	60	60	45	45	30

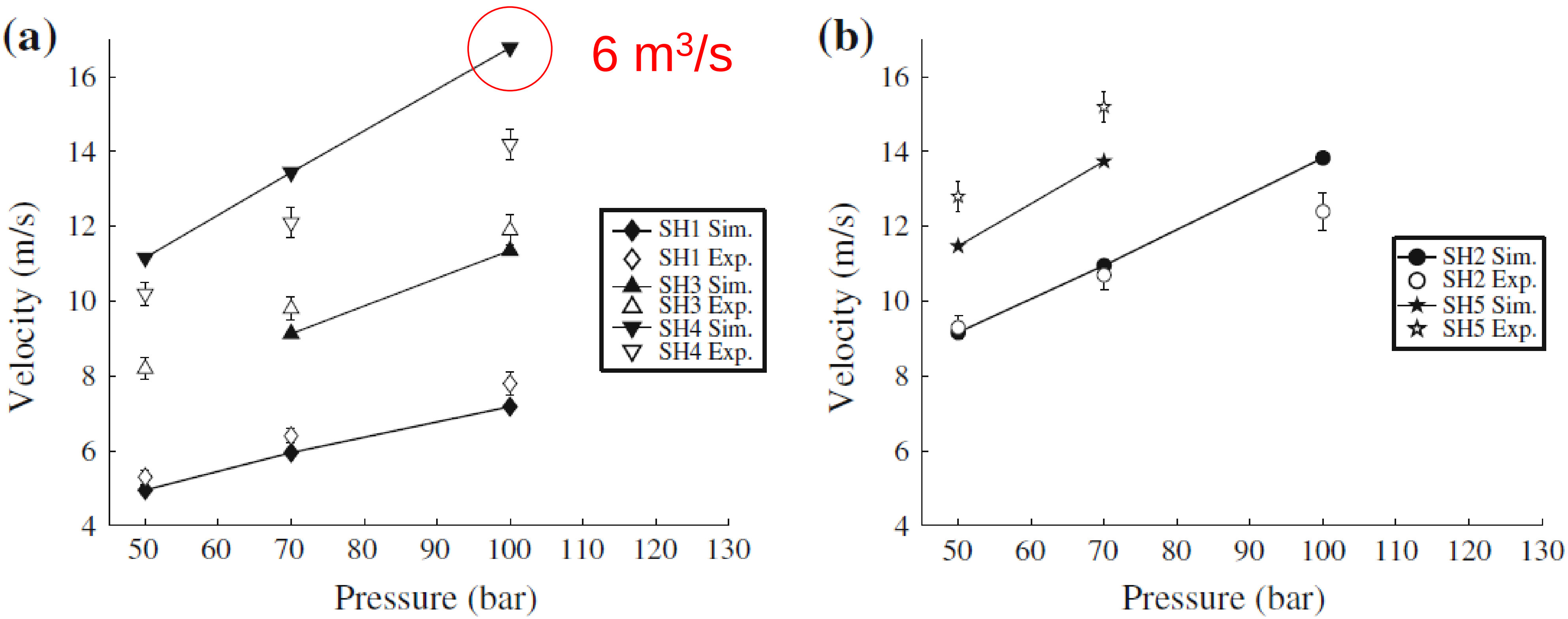
Air entrainment

- Probing the aerodynamic spray-gas interaction in near-range



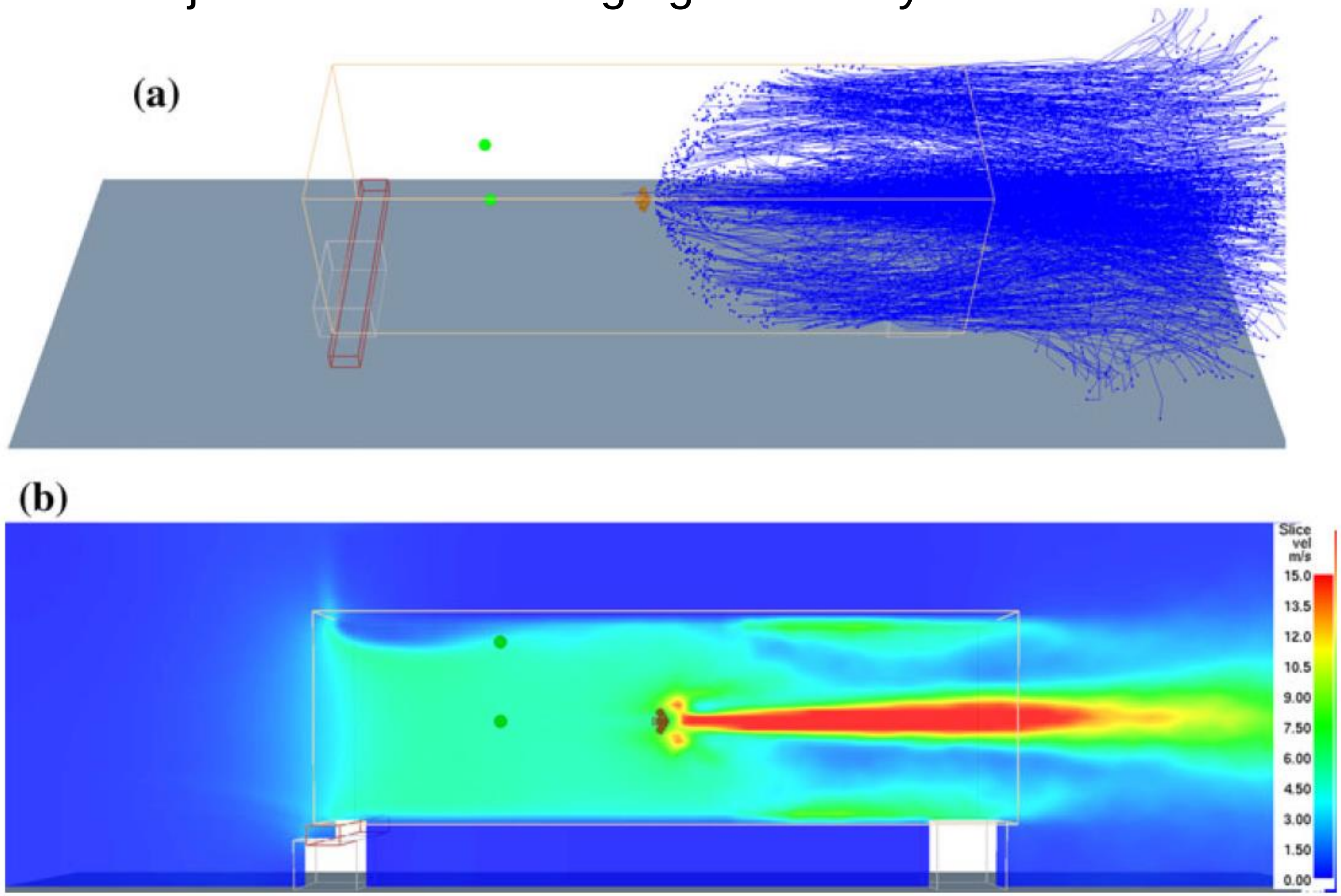
Air entrainment

- Axial gas velocities behind the spray heads



Air entrainment

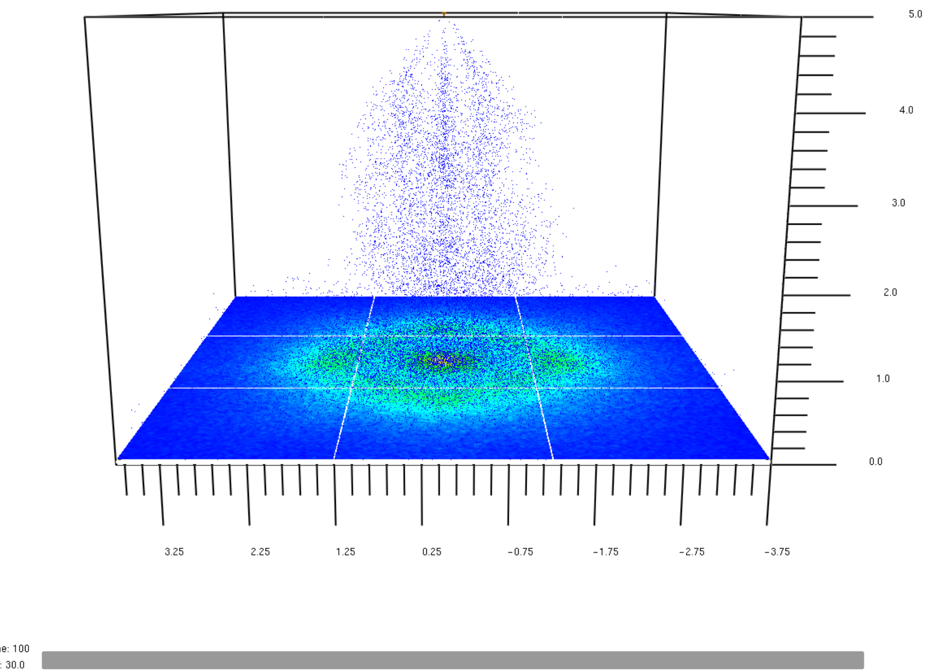
- Particle trajectories and average gas velocity for SH1



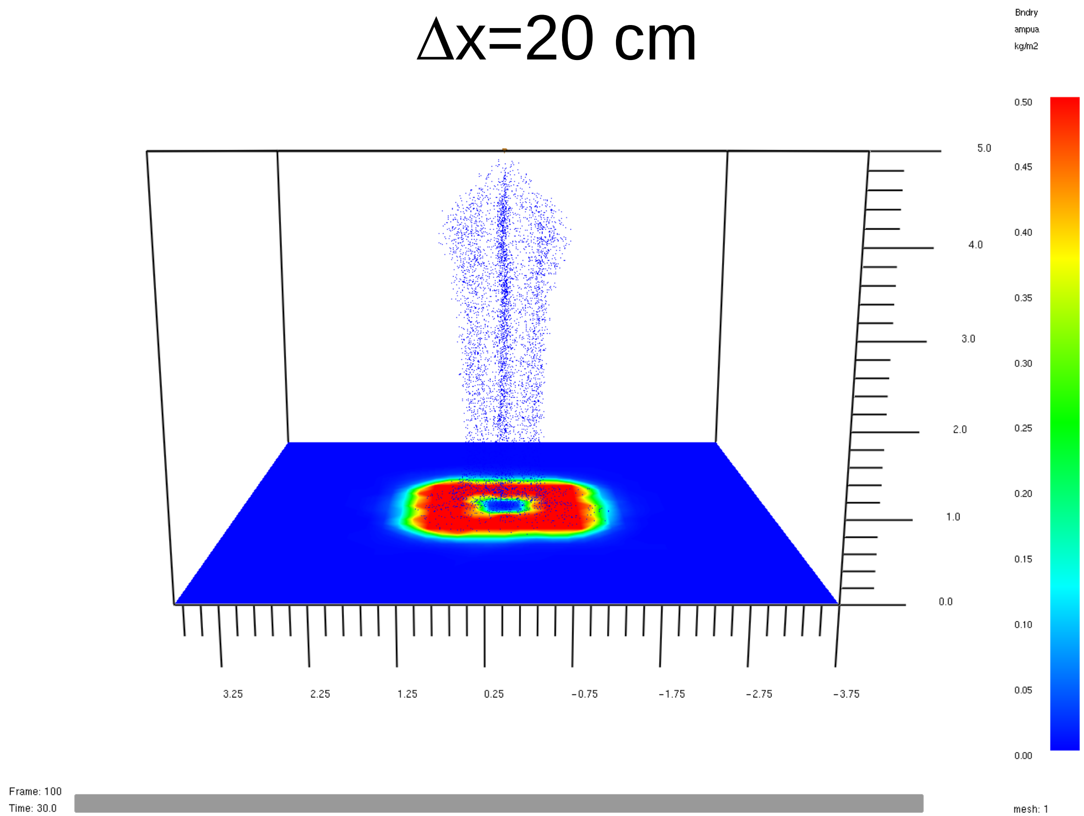
Full-scale water distribution: effect of grid size

- SH3 from 5 m height

Δx=2.5 cm



Δx=20 cm



The computational cost

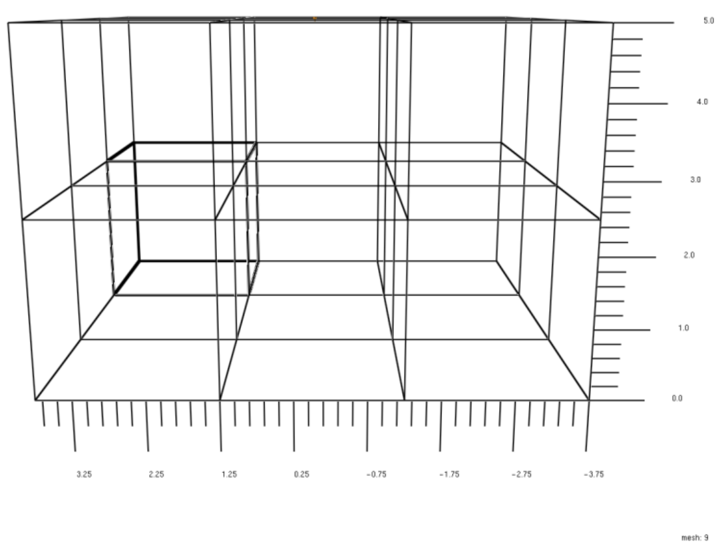
- Domain size: 7.5m x 7.5m x 5m

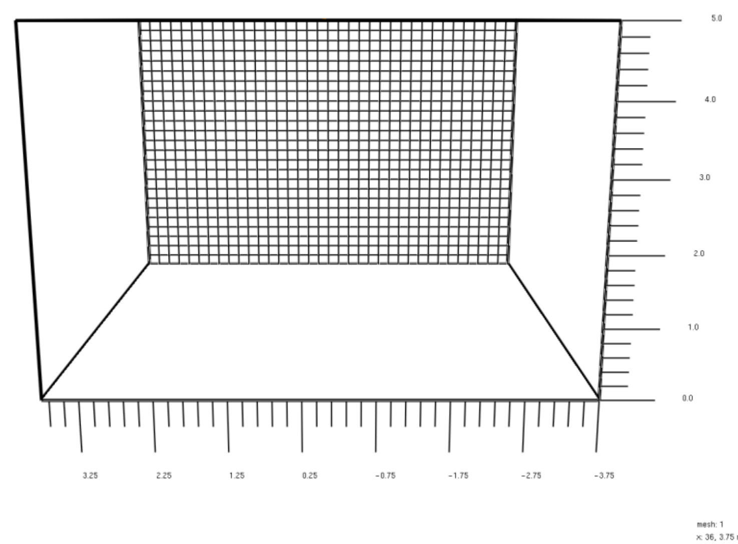
Δx=2.5 cm

- 18 meshes
- 1 million cells per mesh
- 18 million cells total
- 5363h of CPU time (298 h of wall clock time) for 30 s of real time

Δx=20 cm

- 1 mesh
- 32400 cells total
- 2.1h of CPU time for 30 s of real time





Conclusions

- Three high-pressure water mist micronozzles have been characterized according to modified NFPA 750 methodology
- Physically accurate FDS models for the micronozzles have been constructed
- FDS models for multi-orifice spray heads can be constructed based on micronozzle data
- Predicting full-scale spray dynamics accurately requires considerable computational resources

Acknowledgements

- The work was carried out under the Fire Suppression RD project sponsored by the Finnish funding Agency for Technology and Innovation
- Marioff Corporation Oy has supported this research financially and by providing hardware