Karlsruhe Institute of Technology

Fuel preparation in aero engines: Experimental studies and modelling approaches

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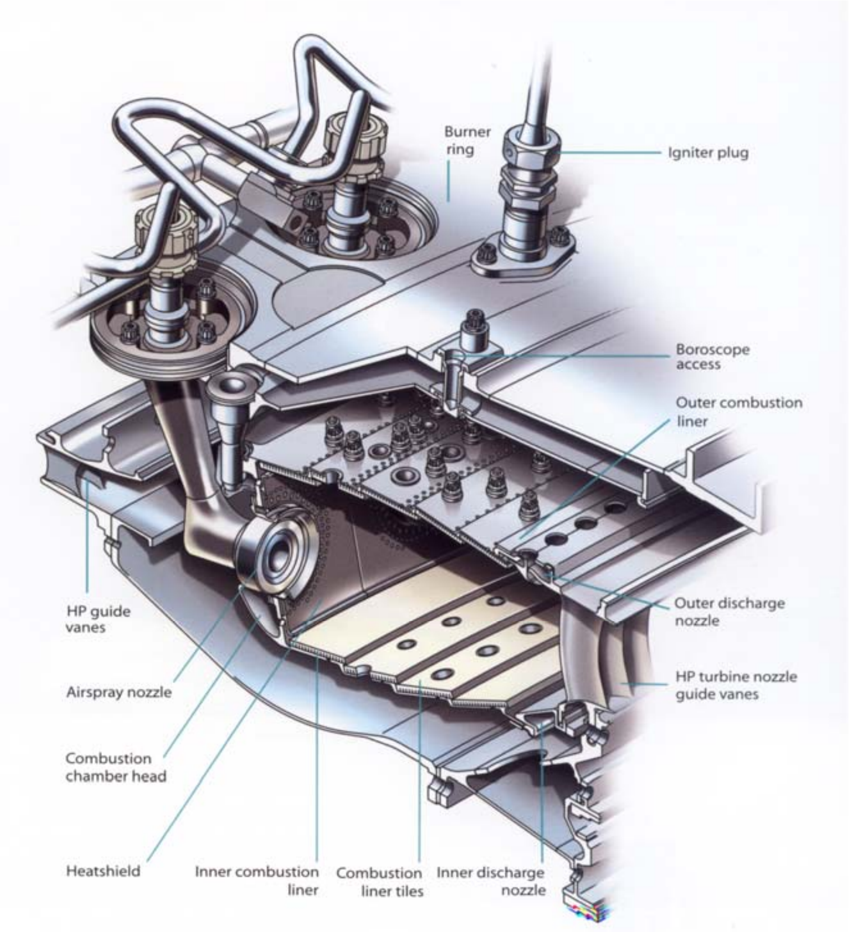
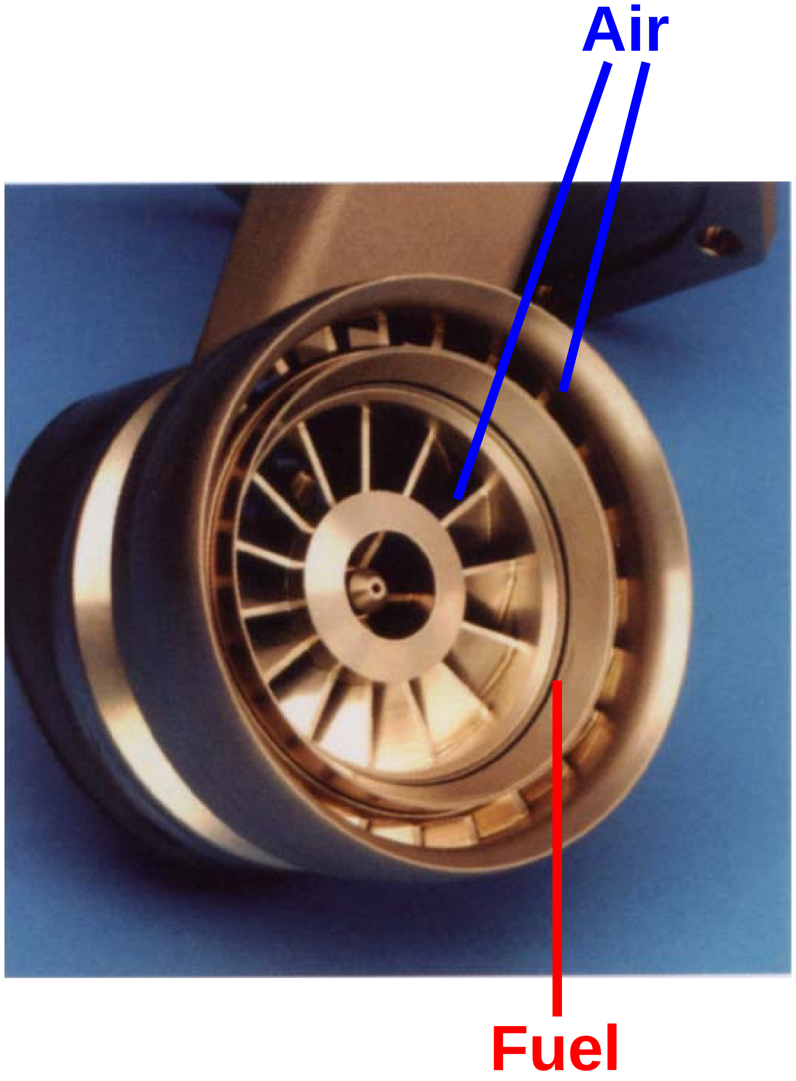
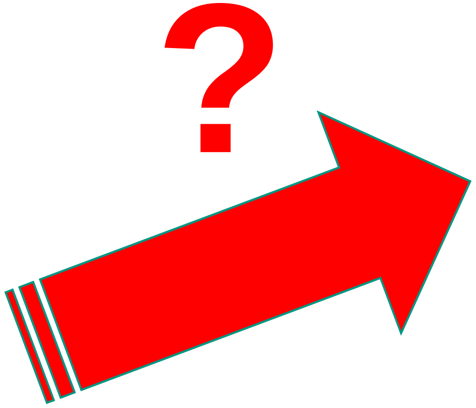
Aero engine combustor and nozzle

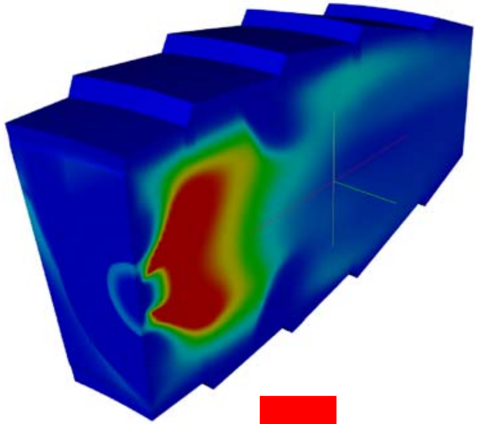




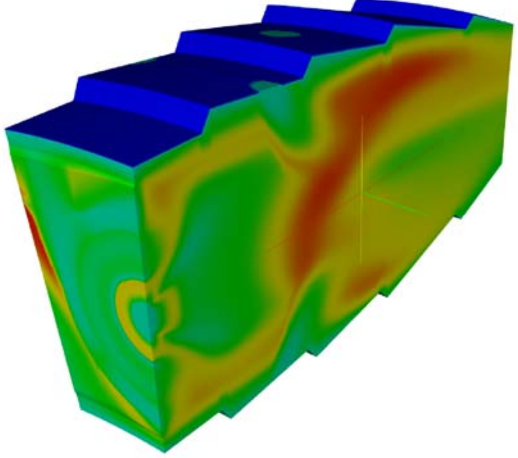
The challenge



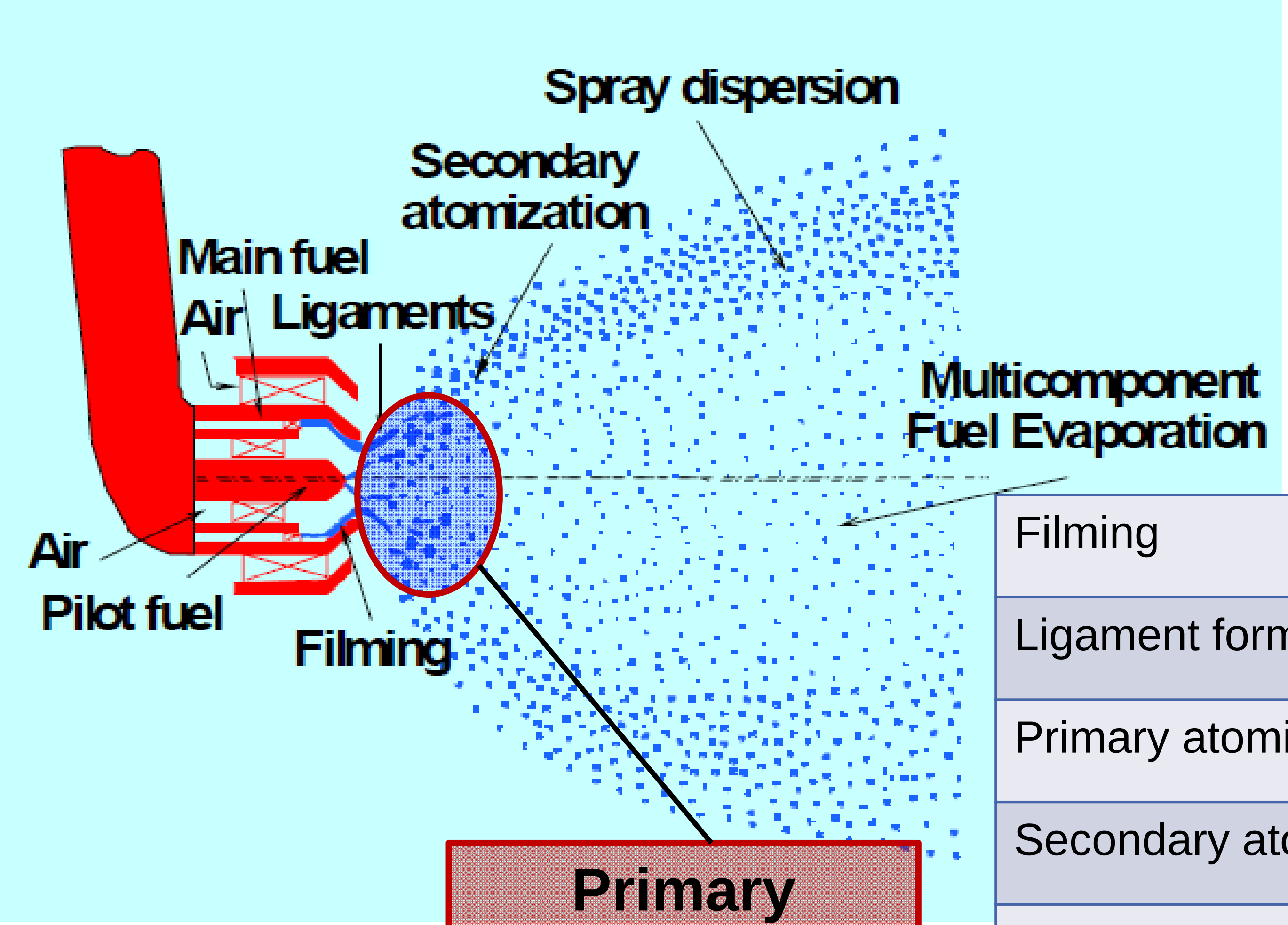
Mixture Fraction



Temperature



Processes involved in atomization



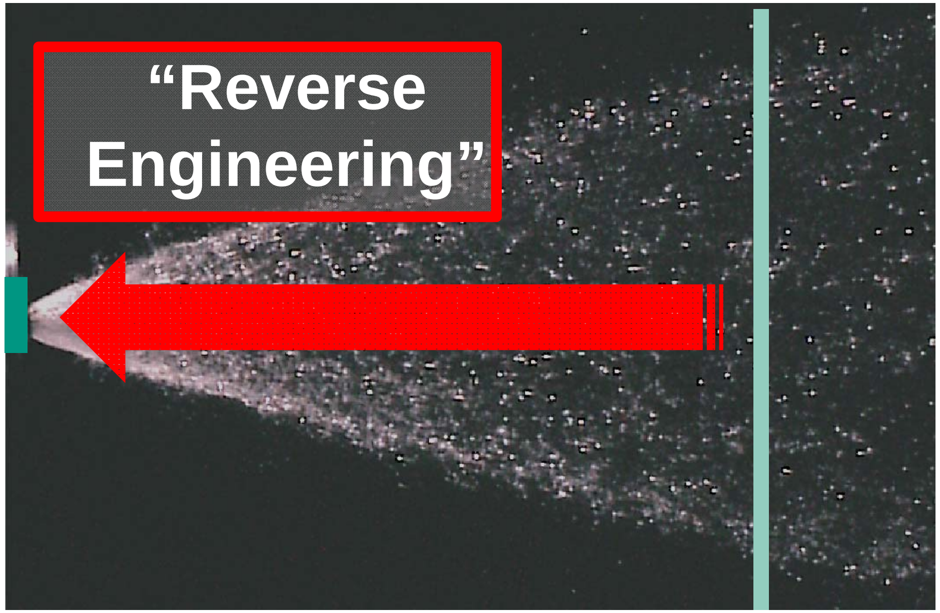
Primary Atomization

Filming	👍
Ligament formation	👎
Primary atomization	👎
Secondary atomization	👍
Spray dispersion	👍
Droplet evaporation	👍

The present procedure

PDA:

- Droplet size
- Droplet velocity



"Reverse Engineering"

"Droplet starting conditions"

Correlations for SMD, e.g. from Lefevbre

SMD = f(AFR, D_{nozzle}, fluid properties, ….)

The missing gap

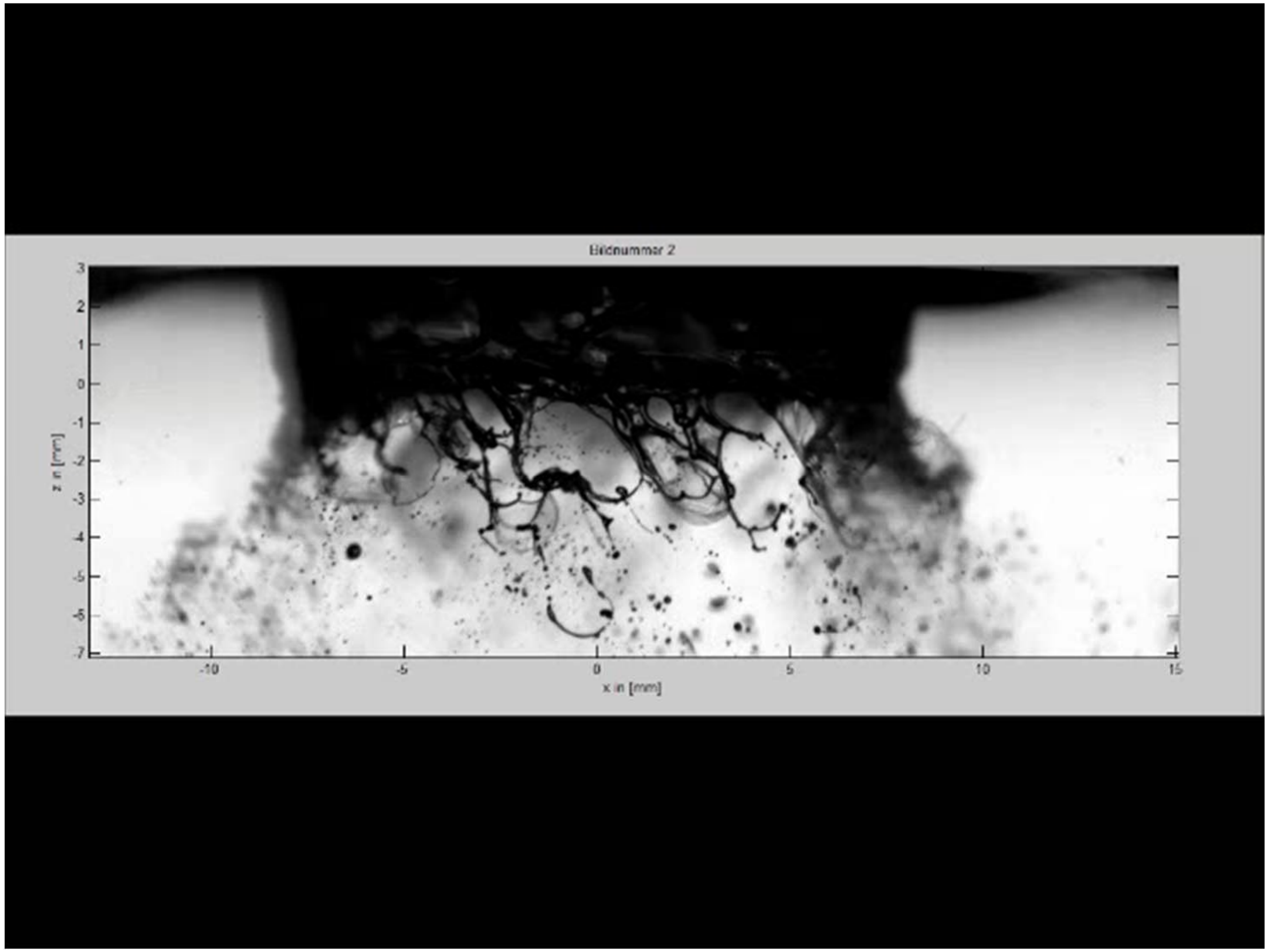
- Expensive PDA measurement (elevated pressure)
- Correlations not reliable
- Design and optimization by trail and error

→

- Virtual injector test rig
  - Numerical prediction based on first principles
  - Exp. validation data

Experimental Studies

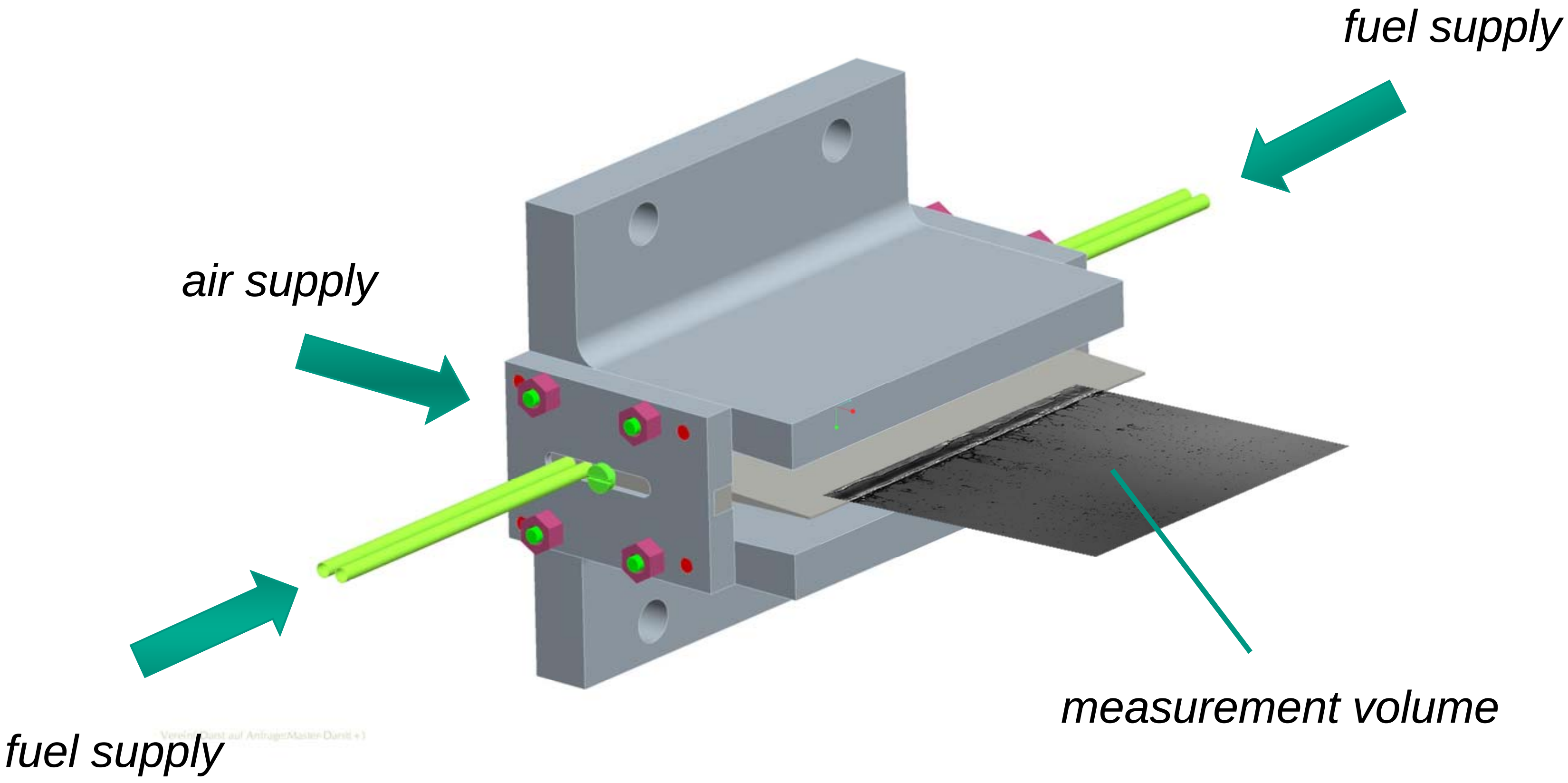
Droplet formation at air-blast atomizer



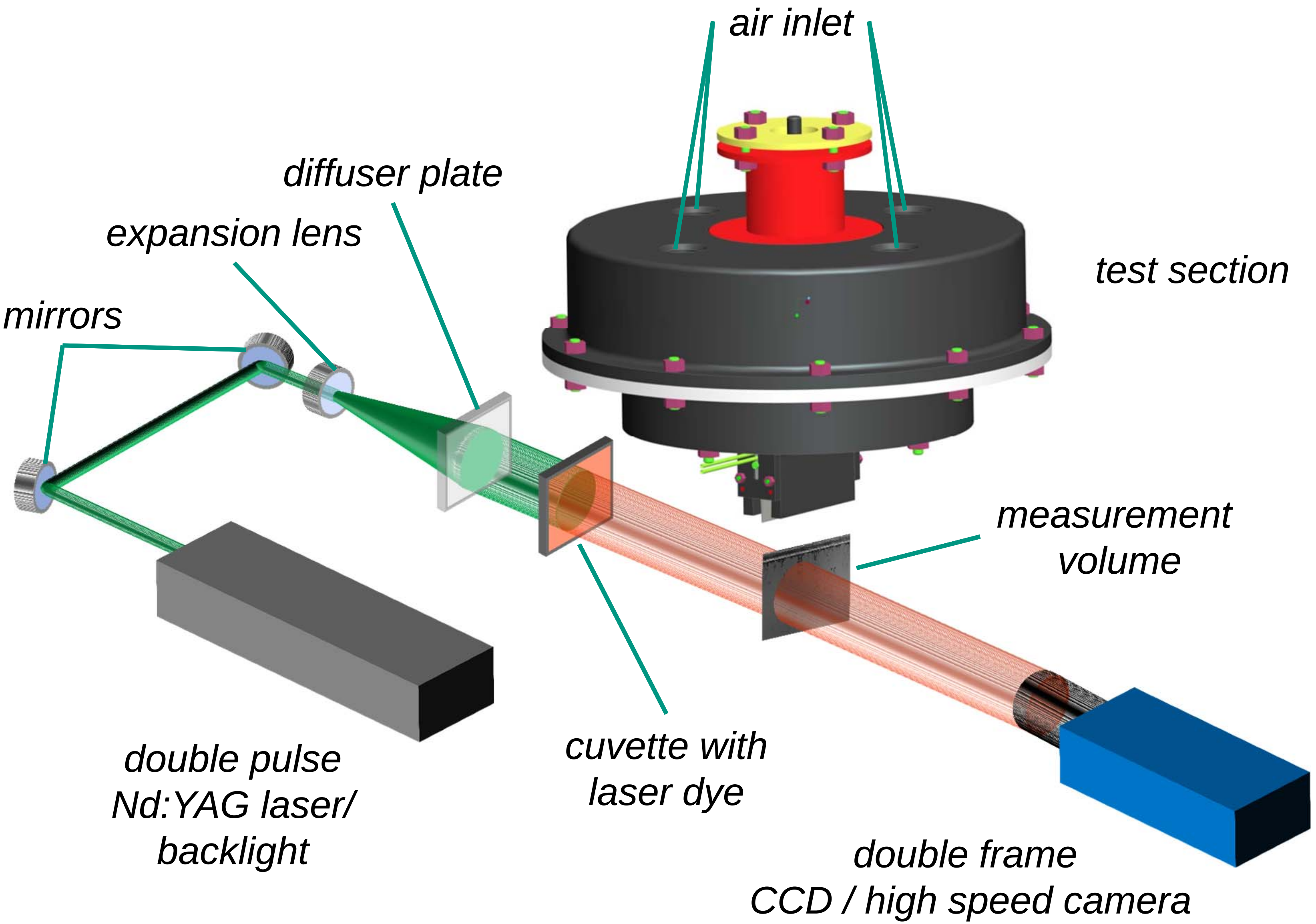
- Wavy film
- Bubble like structures
- Filaments
- Liquid blobs

Planar pre-filmer

- Mean air velocity: 20 to 70 m/s (up to 130 m/s in HDT test rig)
- Liquid loading: 10 to 75 mm²/s



Experimental setup (PTV & High speed)



air inlet

diffuser plate

expansion lens

mirrors

test section

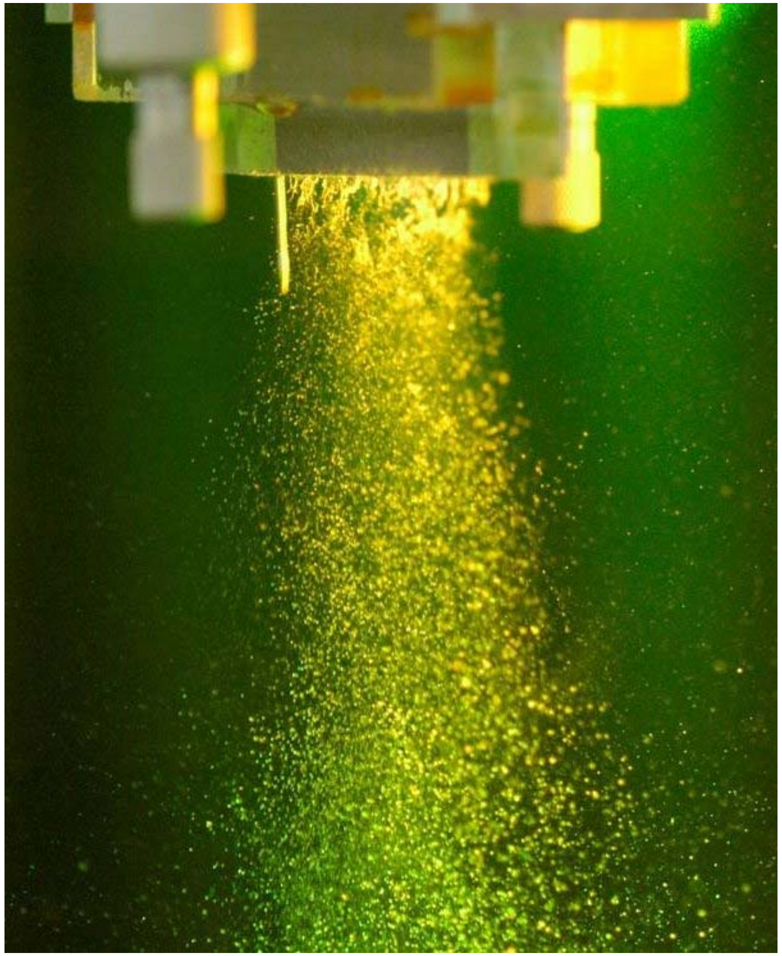
measurement volume

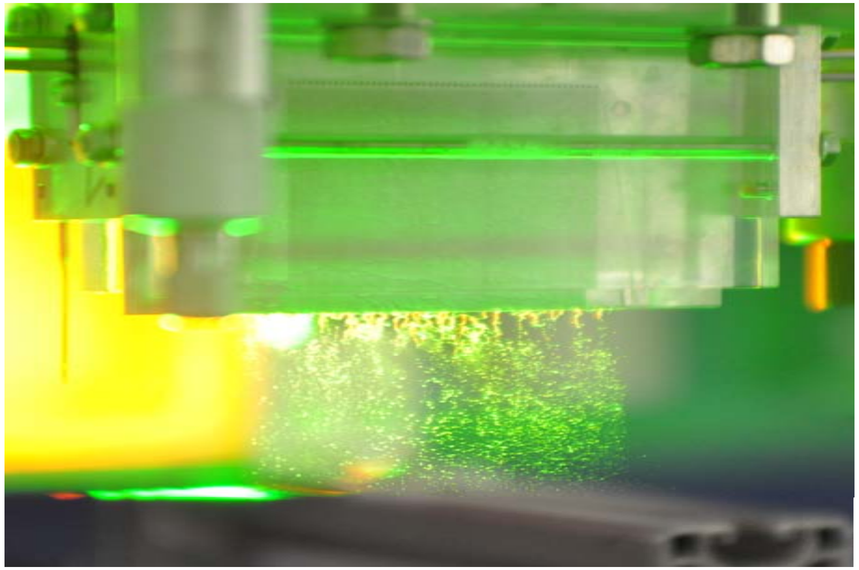
double pulse Nd:YAG laser/ backlight

cuvette with laser dye

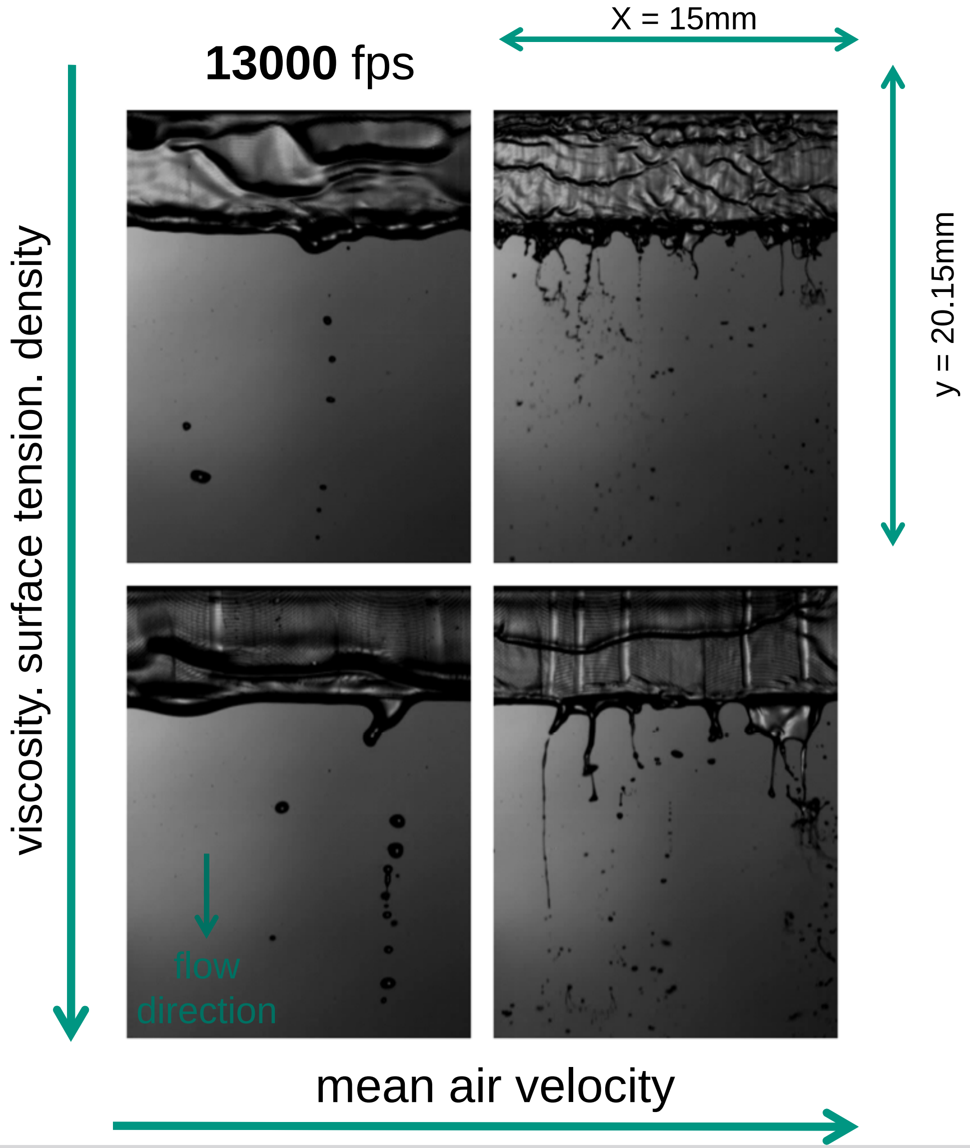
double frame CCD / high speed camera

Planar air-blast atomizer: Back light illumination

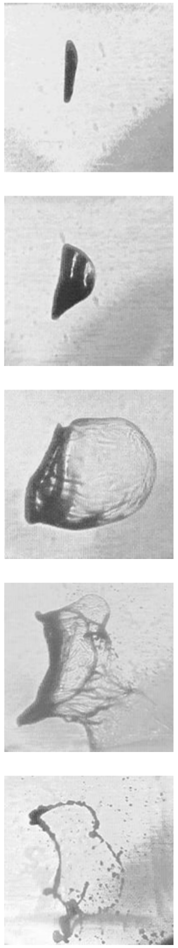




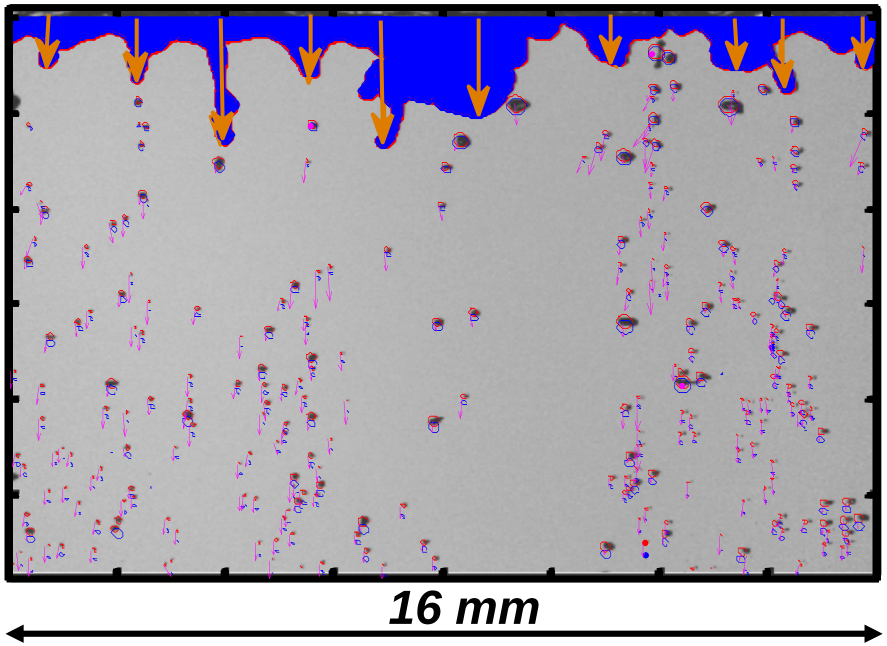
Fluid structures at atomizing edge



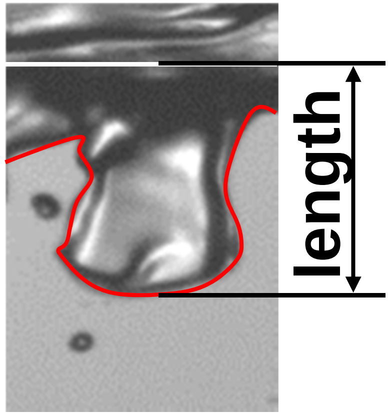
Bag breakup of single droplet

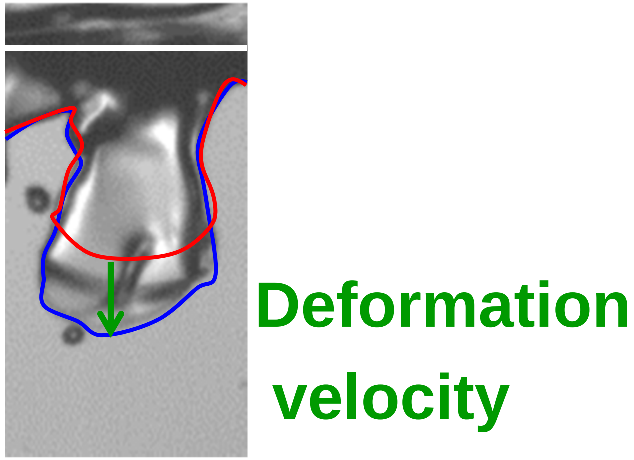


Diagnostics: PTV & ligament tracking



- accumulated liquid, frame 1
- accumulated liquid, frame 2
- particles, frame 1
- particles, frame 2
- **modified PIV**
- **Depth-of-Field correction**





Experimental data

Variation of:

- Air velocity
- Liquid loading
- Liquid properties
  (surface tension, viscosity, density)
- Ambient pressure
- Geometry of prefilmer

Correlations

Unknown parameters:

$f_{breakup}, D_{32}, u_{D,3}$

Non-dimensional quantities:

Input

$$\mathrm{Re}_{\delta_{x\,edge}} = \frac{\rho_g \cdot \overline{u_g} \cdot \delta_{x\,edge}}{\mu_g} \qquad \frac{\rho_l}{\rho_g}$$

$$We_{\delta_{x\,edge}} = \frac{\rho_g \cdot \overline{u_g}^2 \cdot \delta_{x\,edge}}{\sigma_l} \qquad \frac{h}{\delta_{x\,edge}}$$

$$Oh_{\delta_{x\,edge}} = \frac{\mu_l}{\sqrt{\sigma_l \cdot \delta_{x\,edge} \cdot \rho_l}} \qquad \frac{\dot{V}/b}{\delta_{x\,edge} \cdot \overline{u_g}}$$

Output

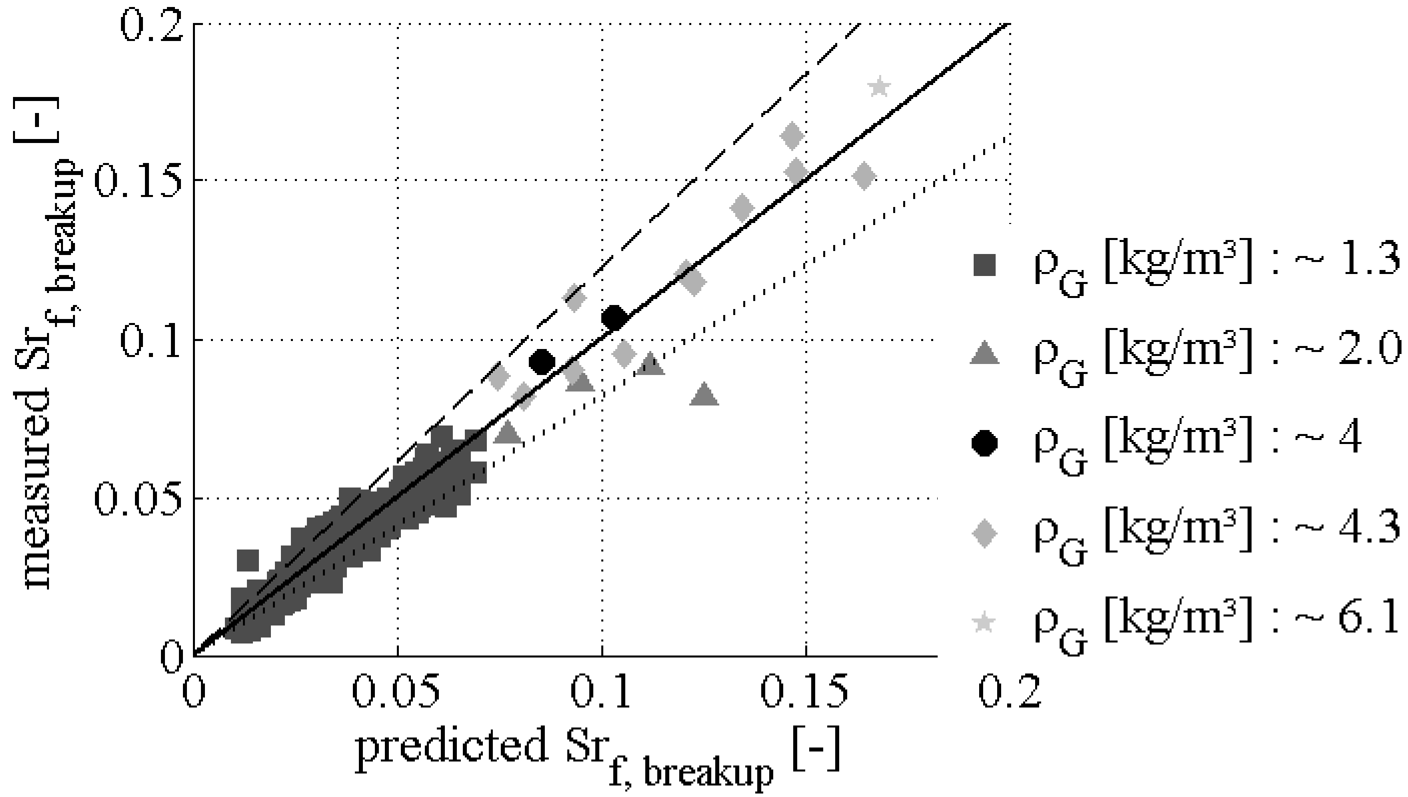
$$Sr_{f,breakup} = \frac{f_{breakup} \cdot h}{\overline{u_g}}$$

$$D_{32} / \delta_{x\,edge}$$

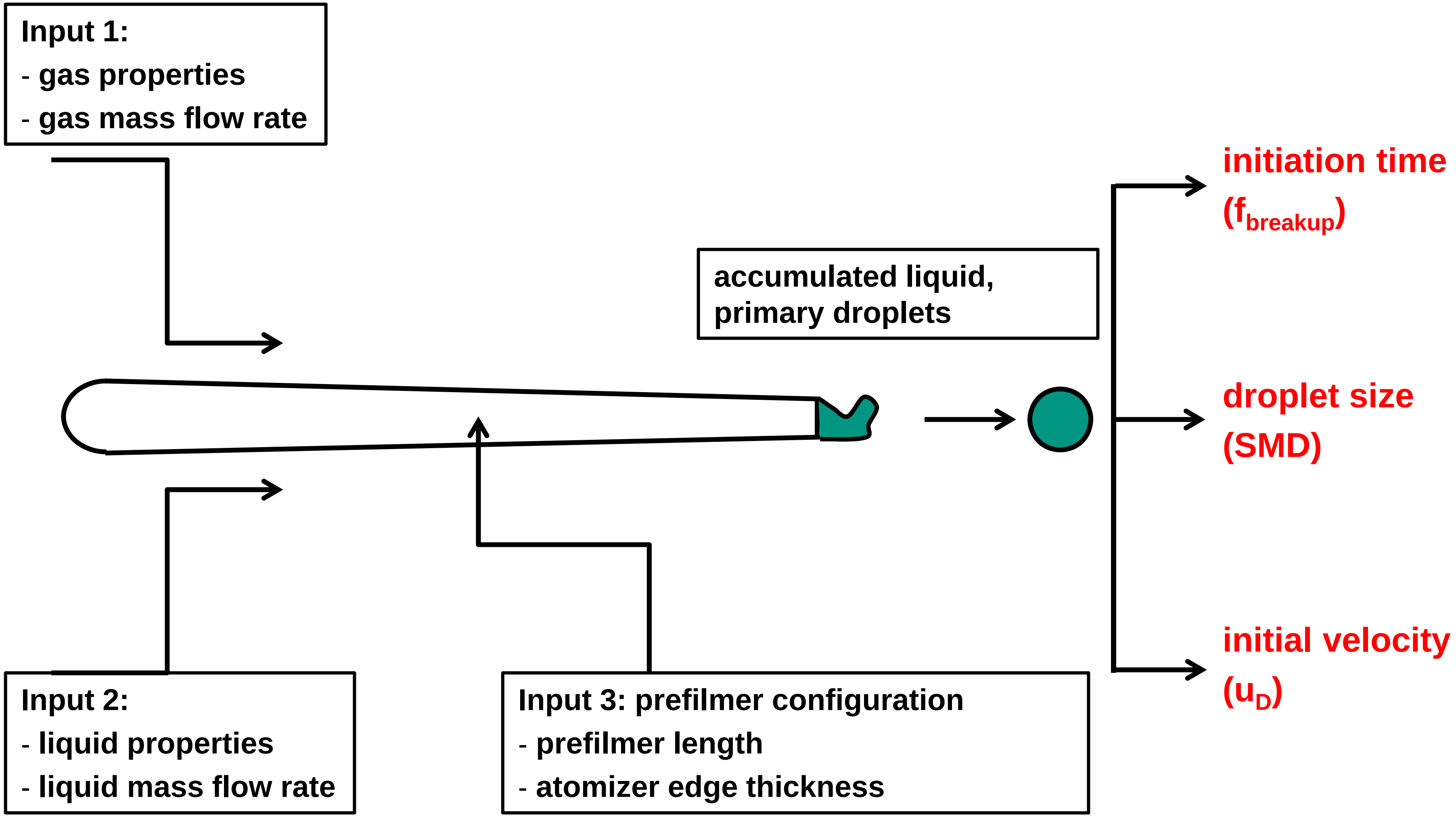
$$u_{D,3} / \overline{u_g}$$

Correlations

$$Sr_{f,breakup} = 2.28 \cdot 10^{-1} \cdot Re_\delta^{-0.15} \cdot We_\delta^{0.54} \cdot Oh_\delta^{-0.06} \cdot \left(\frac{\dot{V}/b}{\overline{u_g} \cdot \delta}\right)^{0.15} \cdot \left(\frac{\rho_l}{\rho_g}\right)^{-0.36}$$



Droplet starting conditions



Input 1:
- gas properties
- gas mass flow rate

accumulated liquid, primary droplets

Input 2:
- liquid properties
- liquid mass flow rate

Input 3: prefilmer configuration
- prefilmer length
- atomizer edge thickness

initiation time ($f_{breakup}$)

droplet size (SMD)

initial velocity (u_D)

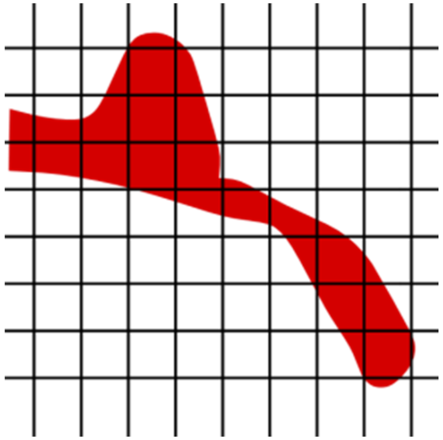
Correlations available from: Gepperth et al.: Ligament and Droplet Characterization in Prefilming Air-Blast Atomization, ICLASS 2012, Heidelberg

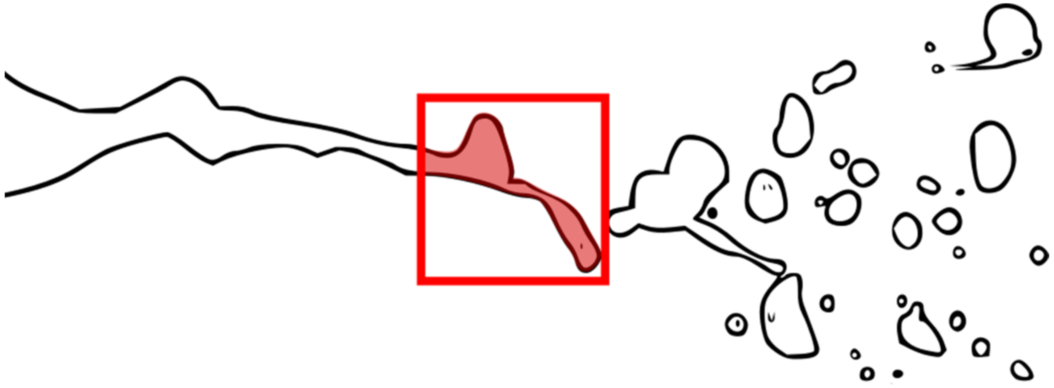
Predictions based on First Principles

Eulerian ↔ Lagrangian Approach

Euerian frame of reference

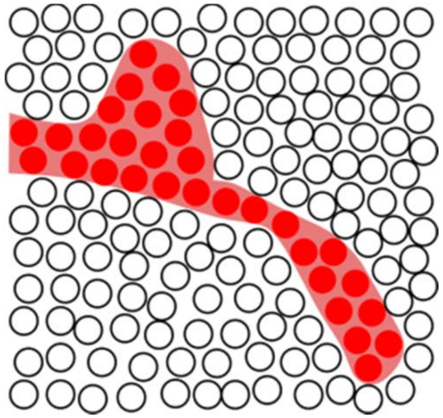
- Grid based
- Methods: Volume of Fluid (VoF), Level Set, …



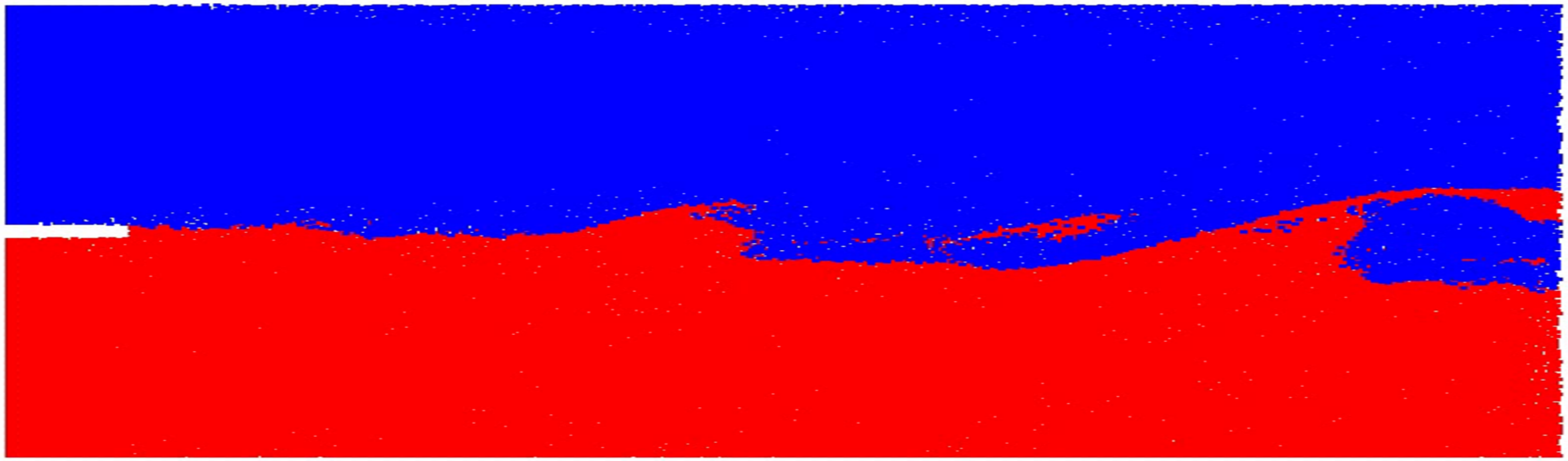


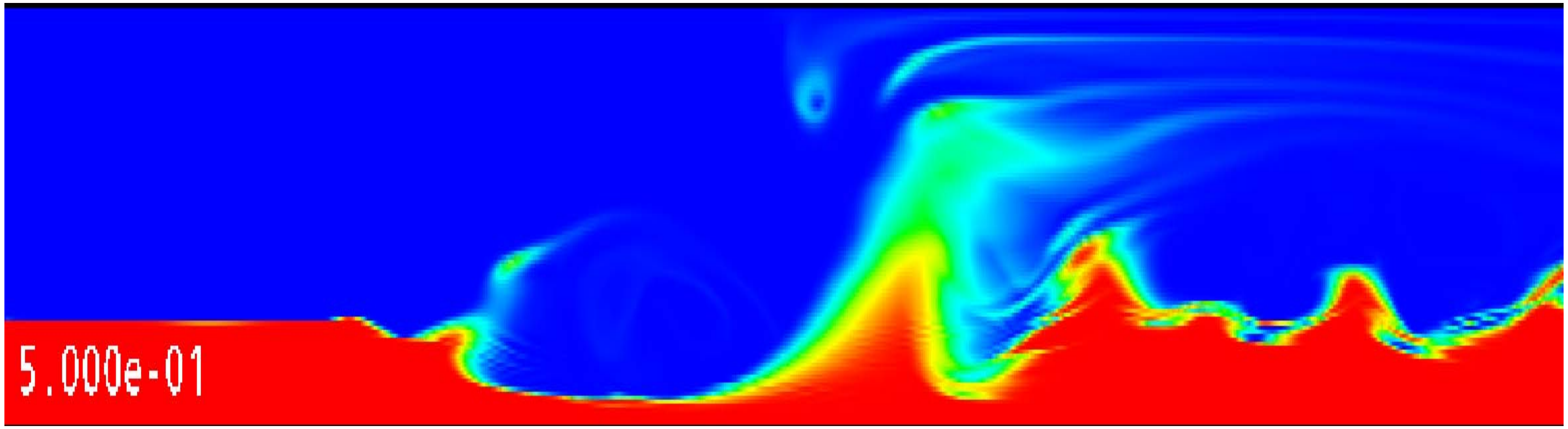
Lagrangian frame of reference

- Particle based
- Methods: Smooth particles hydrodynamics (SPH), Lattice Boltzmann, …



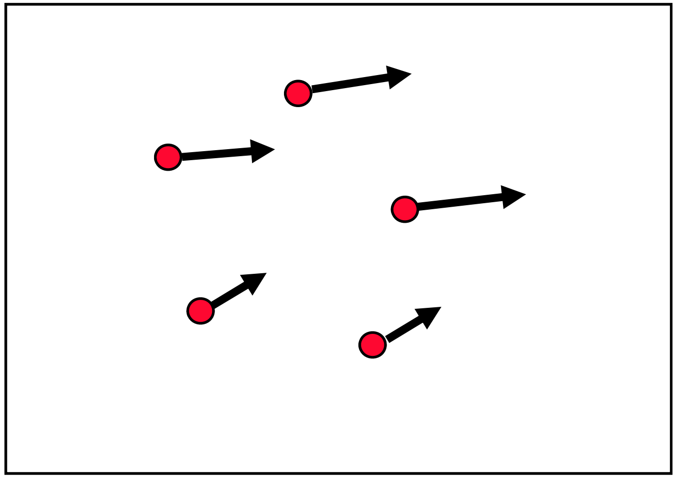
Comparison SPH ↔ VoF





Shear driven liquid film (Hashmi 2011)

Principles of the SPH method

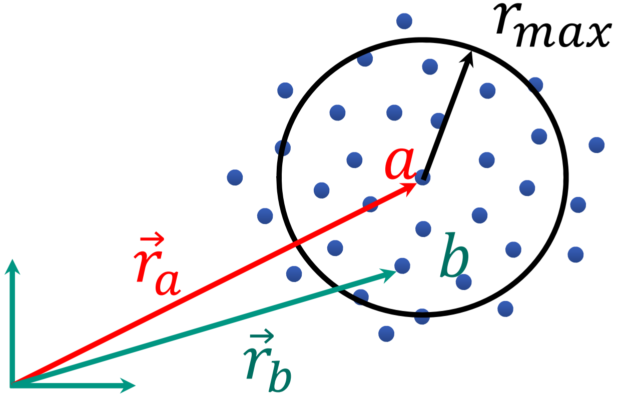


- Fluid is represented by means of moving particles
- Particles represent mass or volume element of the fluid
- Particles represent the local fluid properties (density, velocity, temperature, …)
- Particles are used as spatial discretization points

SPH Principles

- Representation by delta function

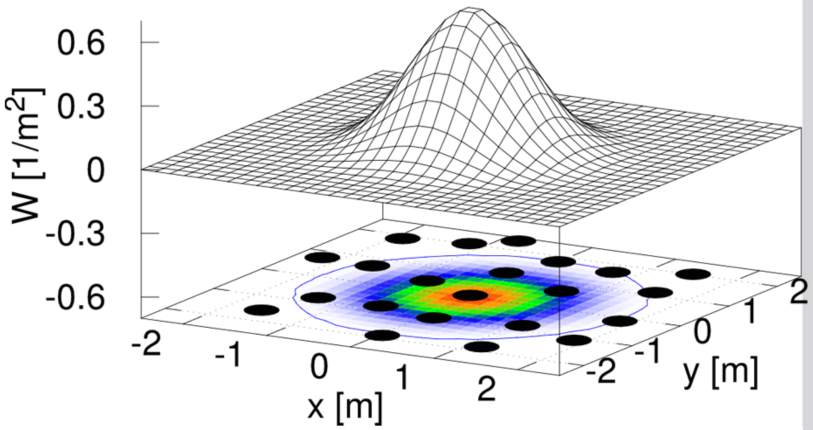
$$f(\vec{r}_a) = \int f(\vec{r}_b)\ \delta(\vec{r}_a - \vec{r}_b)\ d\vec{r}_b$$



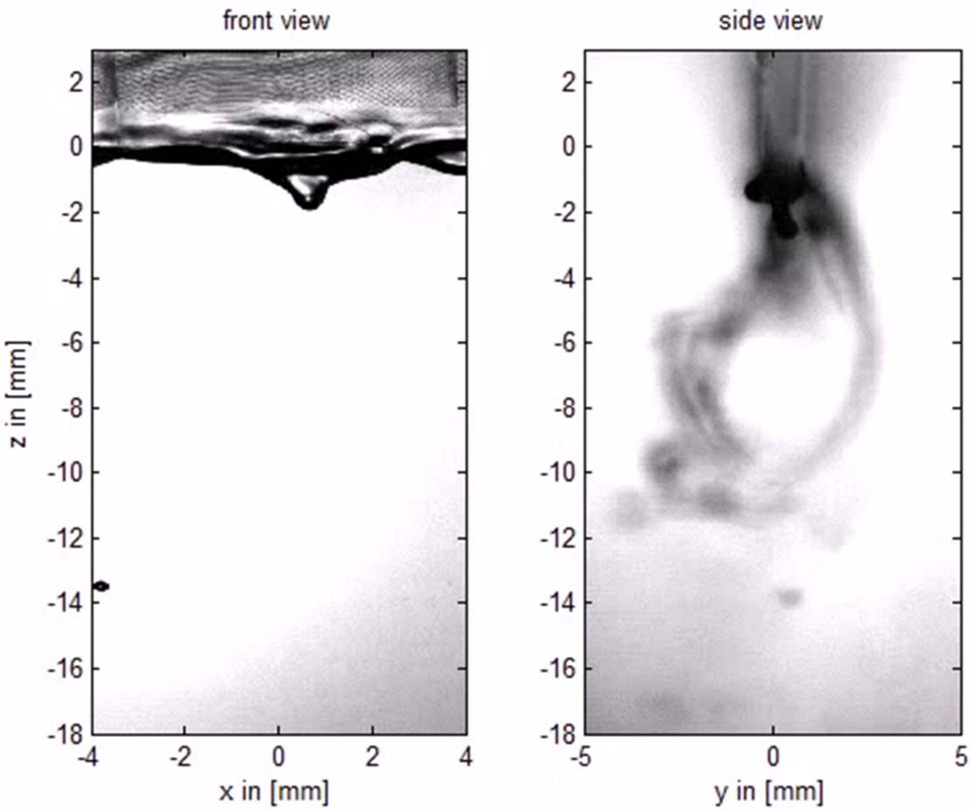
- Approximation by weighted sum

$$f_s(\vec{r}_a) = \sum \frac{m_b}{\rho_b}\, f(\vec{r}_b)\, \mathrm{W}(\vec{r}_a - \vec{r}_b, h)$$

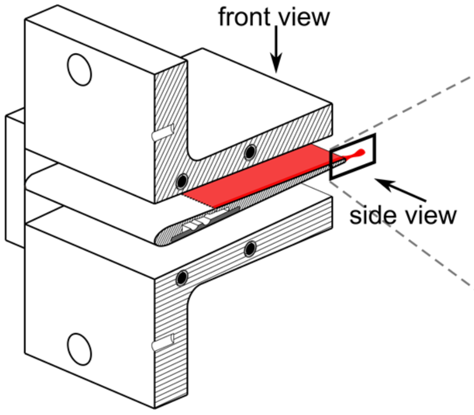
$$\nabla f_s(\vec{r}_a) = \sum \frac{m_b}{\rho_b}\, f(\vec{r}_b)\, \nabla_a \mathrm{W}(\vec{r}_a - \vec{r}_b, h)$$



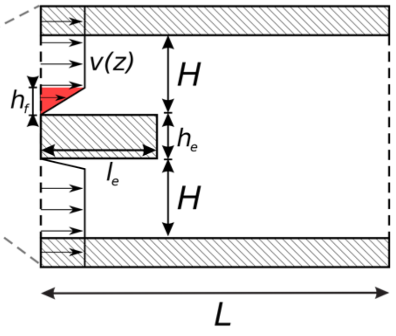
Flow structures at atomizing edge



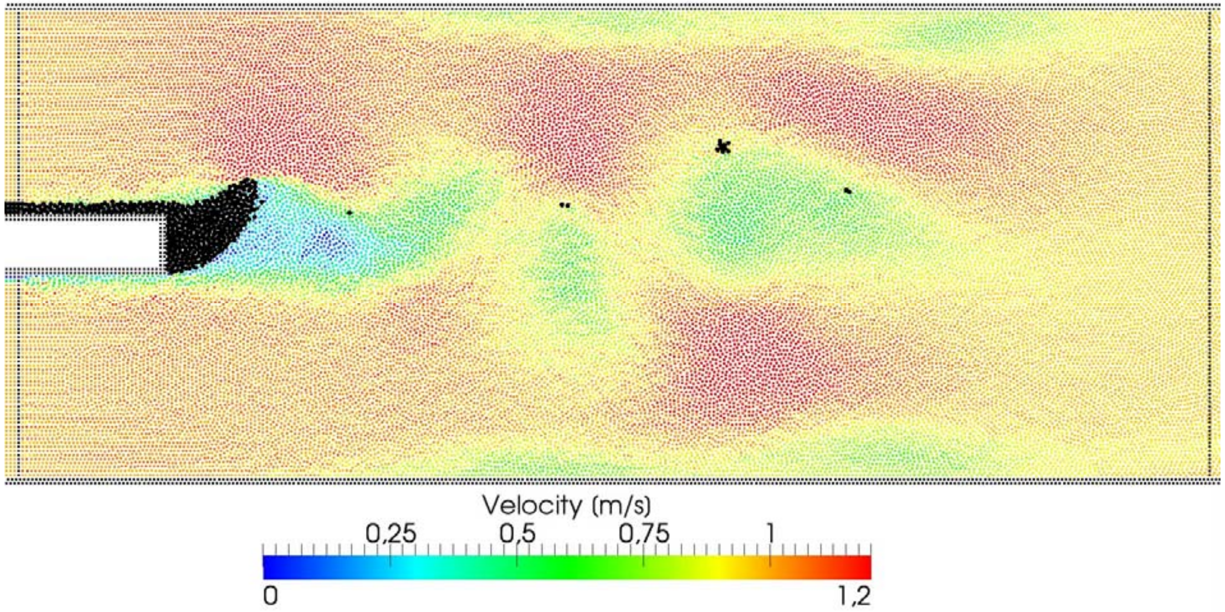
Air-Blast Atomizer Simulation



experimental setup

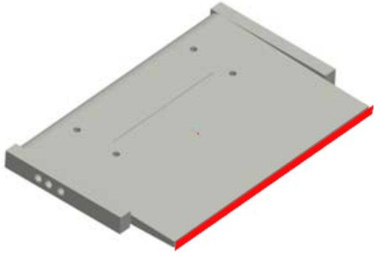


numerical setup

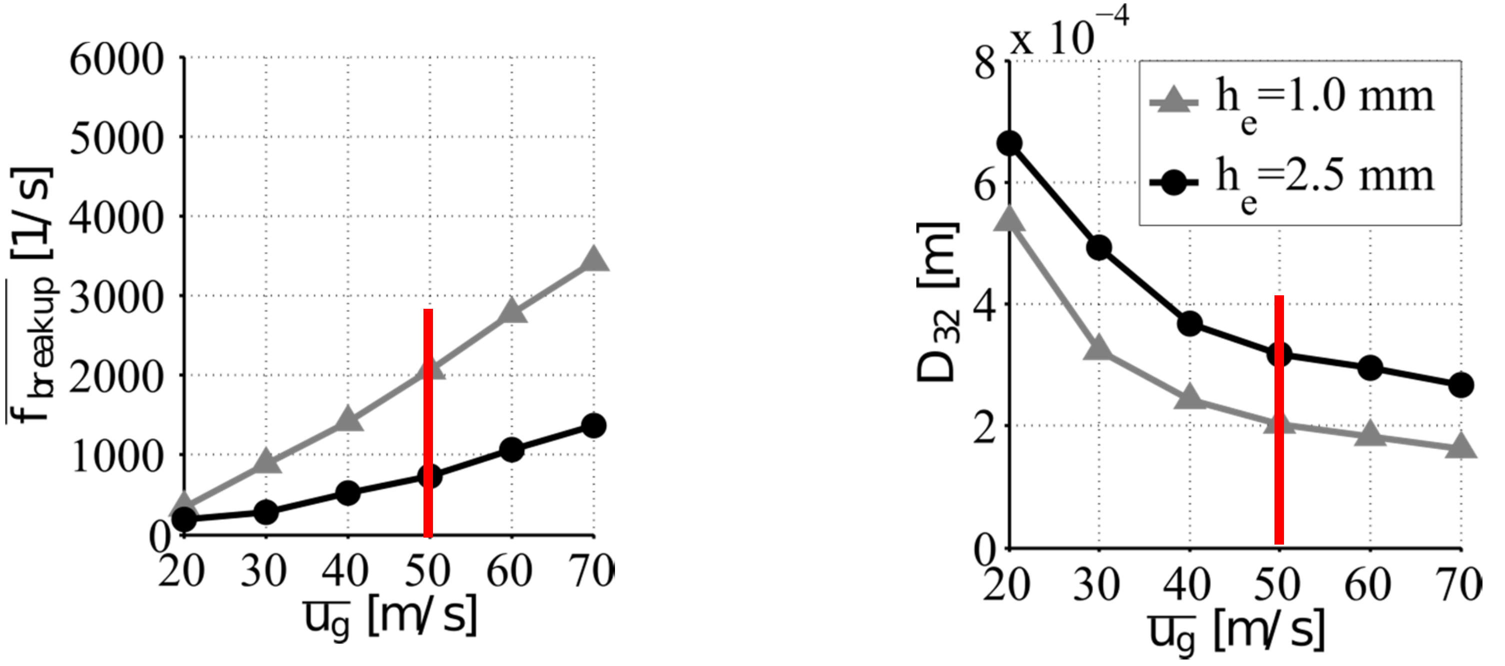


Effect of edge thickness

datum



thick



Shellsol D70, $\dot{V}/b = 25\ \mathrm{mm^2/s}$

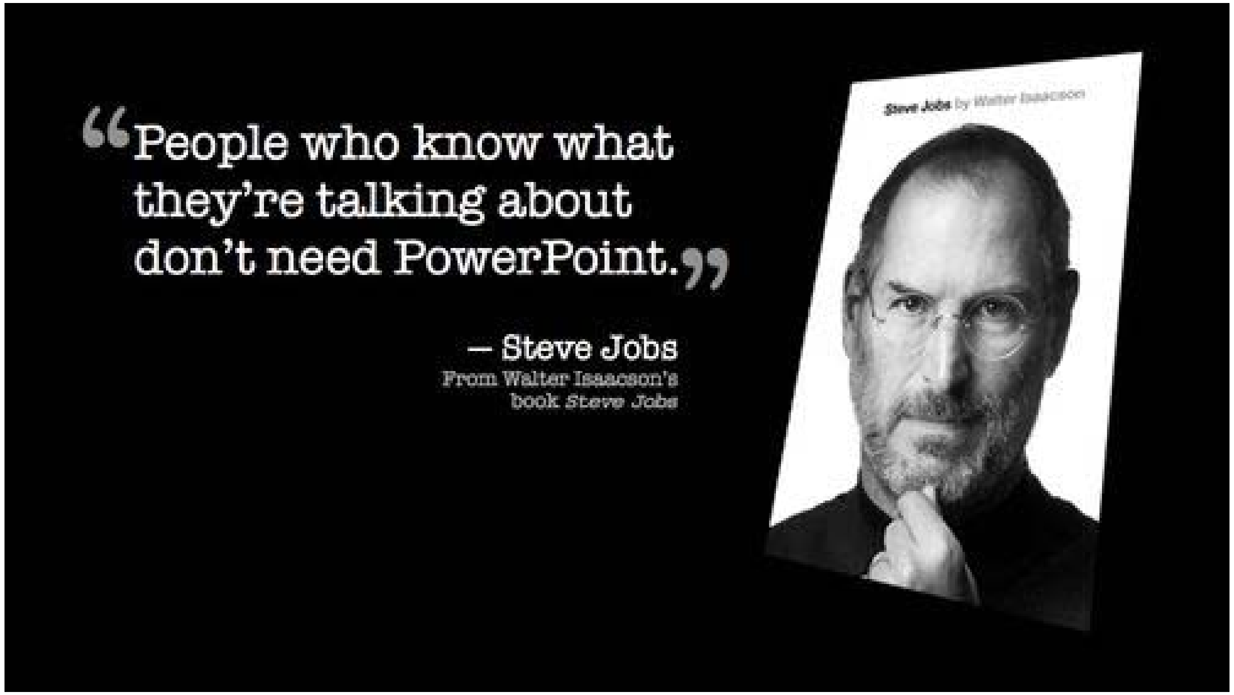
Effect of Edge Thickness

Summary and Conclusions

- **Liquid film flow (waves) do not affect breakup process**
- **Breakup looks similar to bag break of single droplets**
- **Effect of thickness of atomizing edge**
- **Correlations for $f_{breakup}$, SMD, u_D from high speed recordings**
- **Further analysis of exp. data by POD**
- **SPH seems to be promising**

Special Thanks to:

- Samuel Braun
- Sebastian Gepperth
- Corina Hoefler



“People who know what they’re talking about don’t need PowerPoint.”

— Steve Jobs
From Walter Isaacson’s book *Steve Jobs*


Thank You !