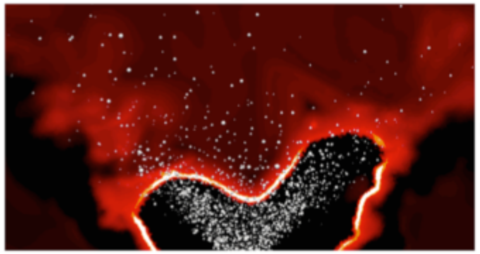
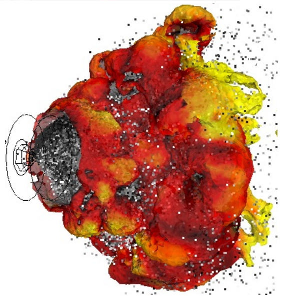
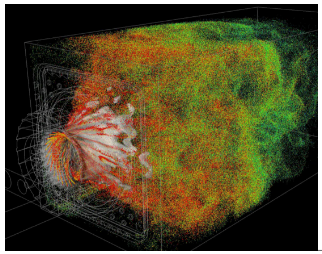
Large Eddy Simulation of two-phase flow combustion



B. Cuenot[1]
E. Riber[1],O. Vermorel[1],L.Y.M. Gicquel[1],G. Staffelbach[1],F. Duchaine[1],
A. Dauptain[1],T. Poinsot[2]





[1] CERFACS - CFD Team, Toulouse
[2] IMFT, Toulouse

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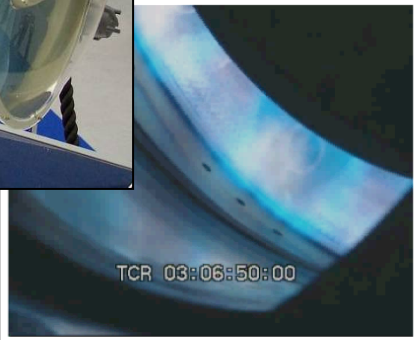
Benedicte.Cuenot@cerfacs.fr

Two-phase flow combustion

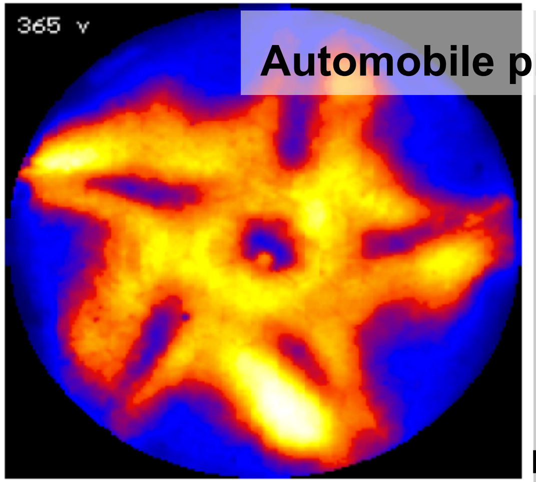
Aeronautical propulsion

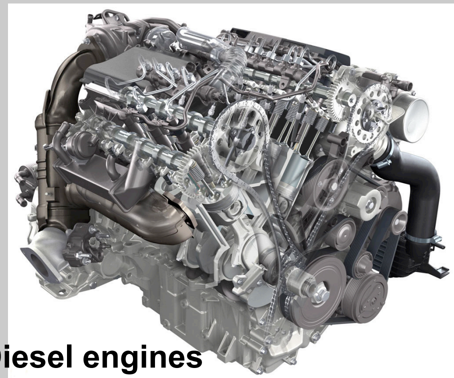
copyright Snecma



Rocket propulsion

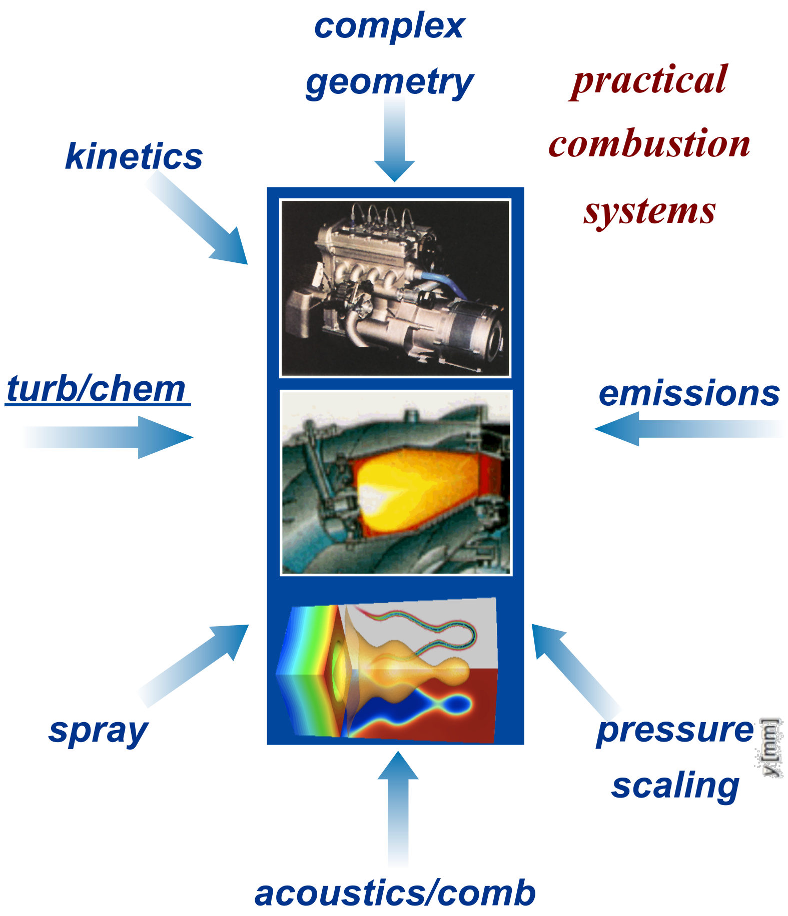
Automobile propulsion



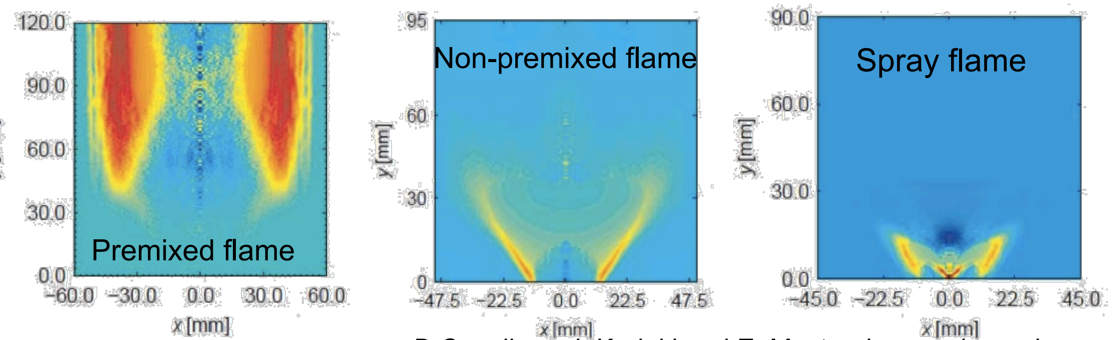


Diesel engines

Impact of two-phase flow on combustion



- **Flame structure**
- **Pollutant emissions**
- **Ignition & stability**
- **Thermo-acoustic instabilities**
- **Liquid films**



D.Cavaliere, J. Kariuki and E. Mastorakos under review

Advanced CFD and ***Massively parallel*** computer architectures offer a clear potential for time and cost reductions of the design chain while providing ***more accurate predictions***

Compressible Navier-Stokes equations, LES approach

Unstructured/hybrid meshes

Explicit in time

Centered schemes

- Finite Volumes / Finite Elements ($2^{nd}/3^{rd}$ order[a])

SGS models : Smagorinsky(dynamic)/WALE[b]

NSCBC[c] boundary cond. + wall laws

Reduced[d] or tabulated[e] chemical kinetics

Thickened flame turb. combustion model (TFLES)[f]

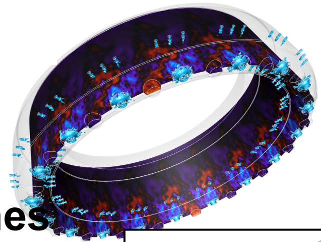
Lagrangian and Eulerian approaches for the spray

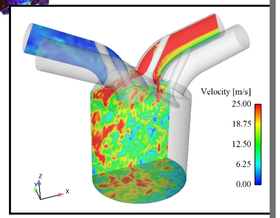
Massively parallel

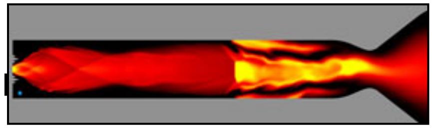
Jointly developed by IFPEN and CERFACS

Applications

- Gas turbines
- Aeronautical engines
- Piston engines
- Statoreactor
- Rocket engines
- Furnaces
- Heat exchanger







[a]Colin O. & Rudgyard M., Journal Comp. Physics, 2000

[b]Nicoud F. & Ducros F., Flow, Turb. Combustion, 1999

[c]Poinsot T. & Lele S., Journal Comp. Physics, 1992

[d]Franzelli B. et al., Combust. Flame, 2010

[e]Fiorina B. et al., Combust. Flame, 2010

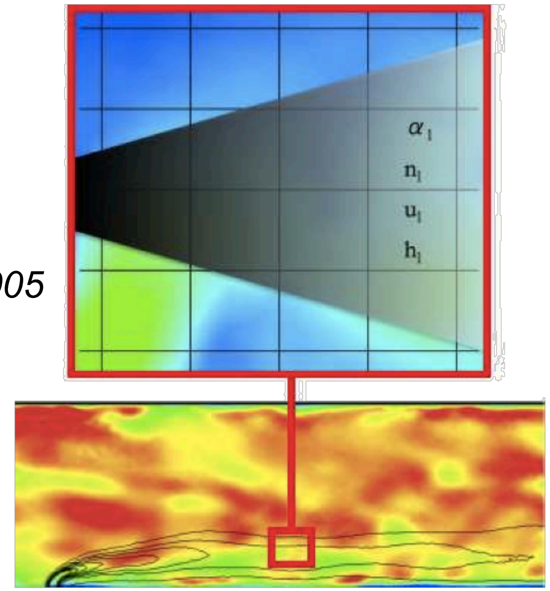
[f]Colin O. et al. Physics of Fluids, 2000

Compressible Navier-Stokes equations, LES approach

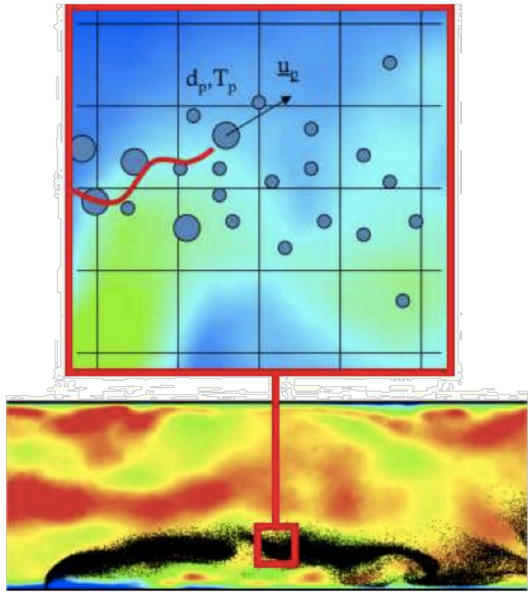
Jointly developed by IFPEN and CERFACS

Mesoscopic Euler (statistical approach)

Février et al JFM 2005



Lagrange



Liquid phase in a jet in cross flow

F. Jaegle Phd Thesis 2010

[a]*Colin O. & Rudgyard M., Journal Comp. Physics, 2000*

[b]*Nicoud F. & Ducros F., Flow, Turb. Combustion, 1999*

[c]*Poinsot T. & Lele S., Journal Comp. Physics, 1992*

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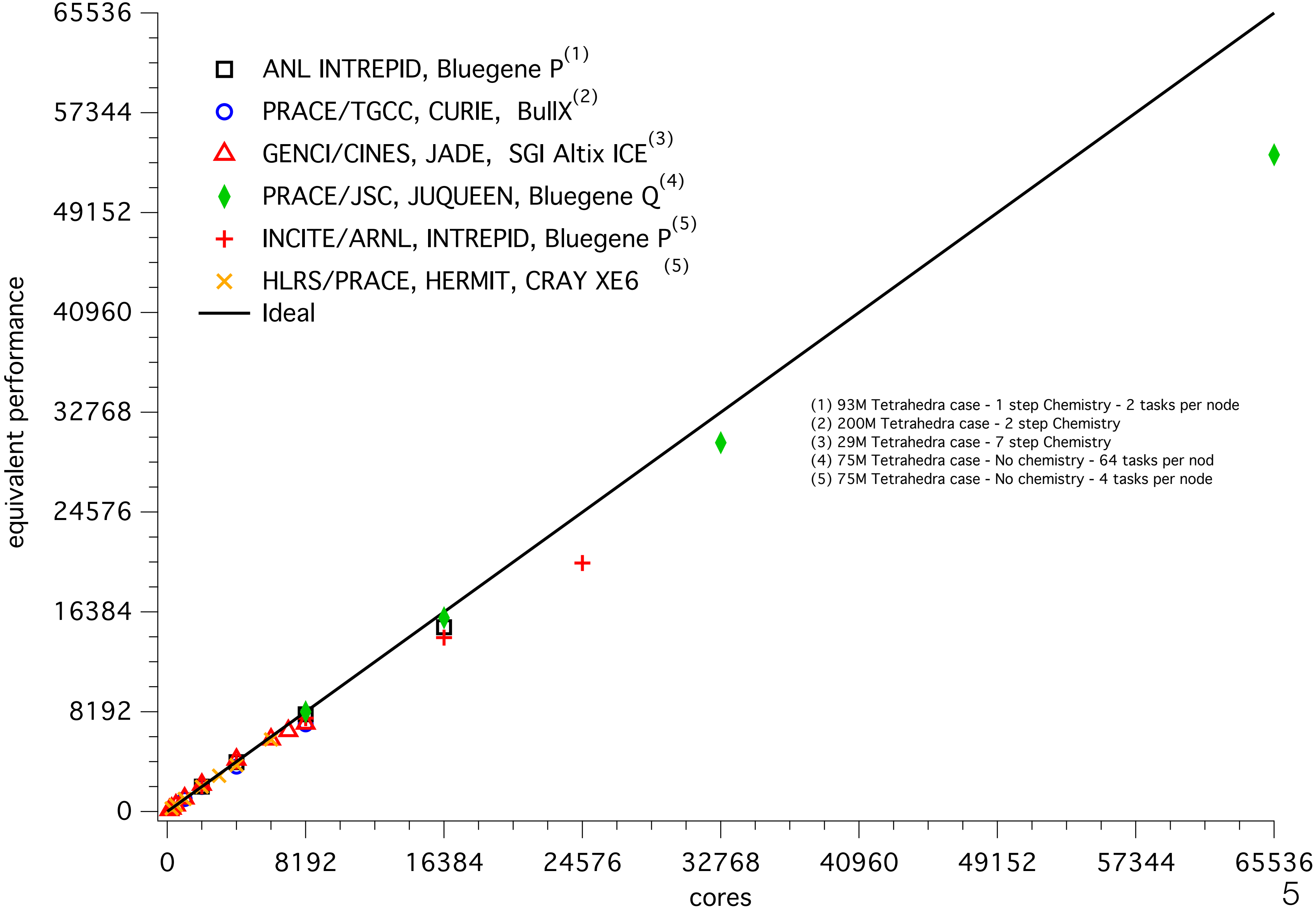
[f]*Colin O. et al. Physics of Fluids, 2000*

AVBP and HPC

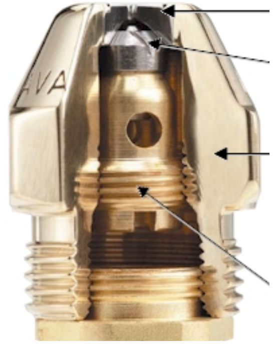
HPC is a key point!

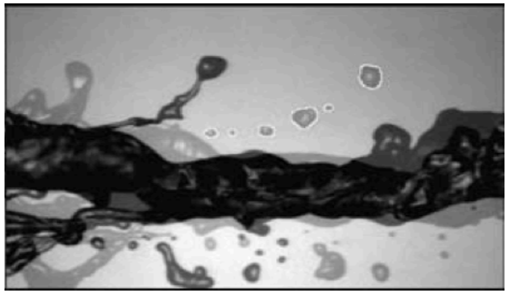


OUTLINE

I - Modelling issues of two-phase combustion

- Eulerian formulation : Random Uncorrelated Motion
- Polydispersion
- Evaporation
- Fuel Injection



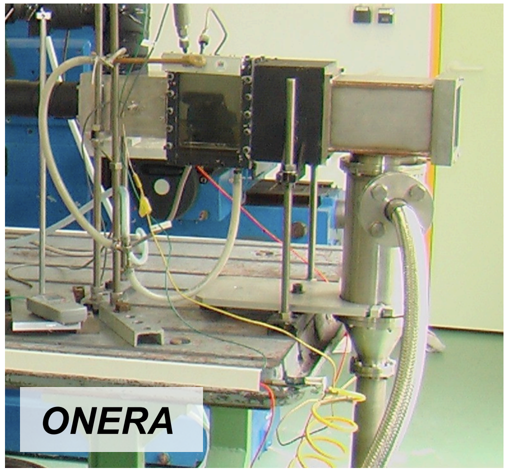


II – A lab-scale experiment

- Cambridge burner

III - Application to a complex geometry

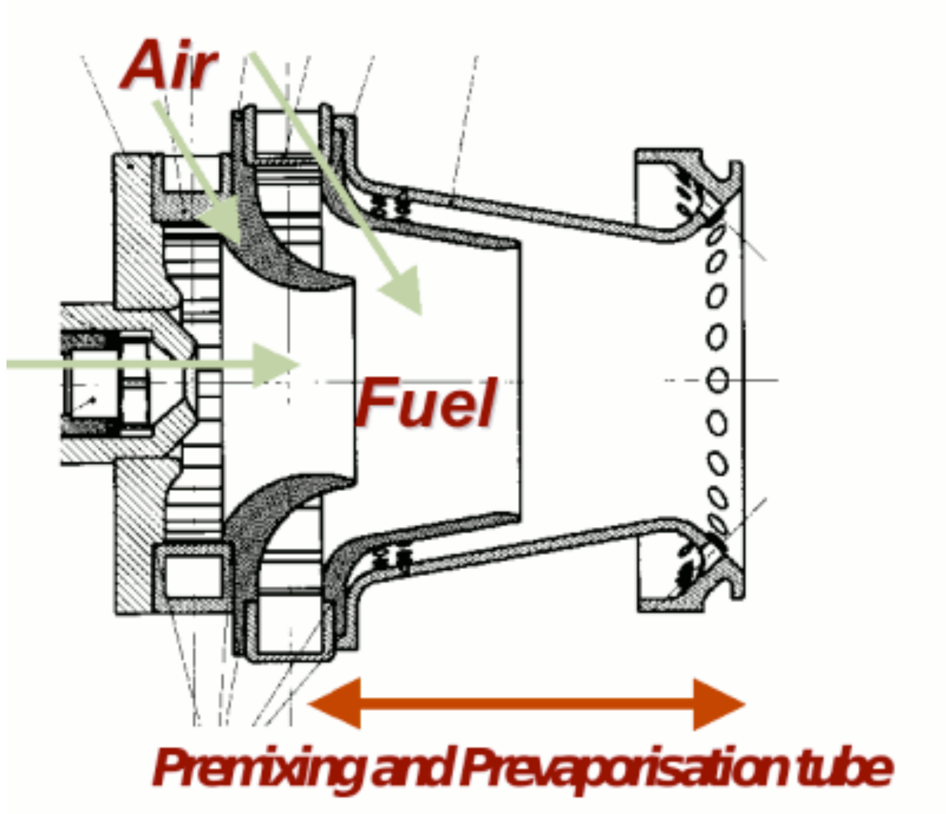
- MERCATO burner

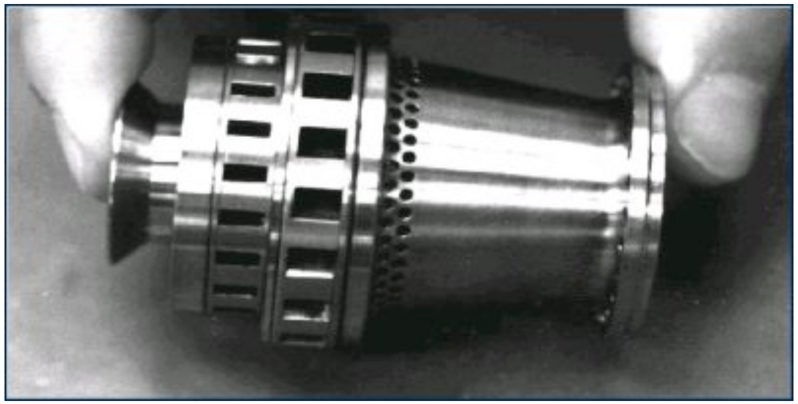


IV – Conclusions

Aeronautical injection systems:

LP injection system (RR)



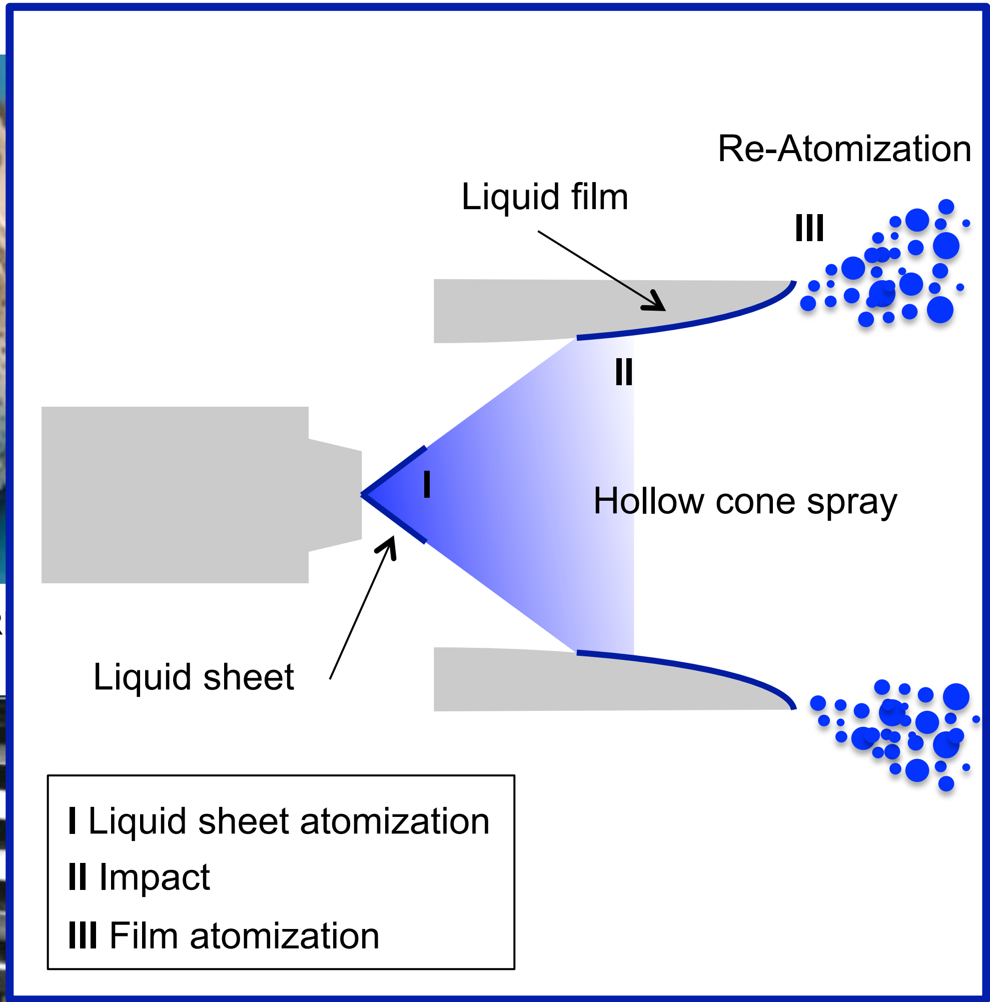


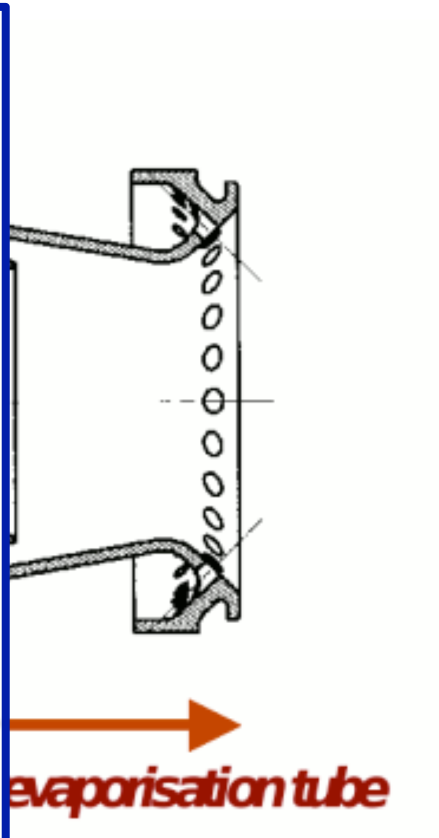
LPP Injection System (SNM)

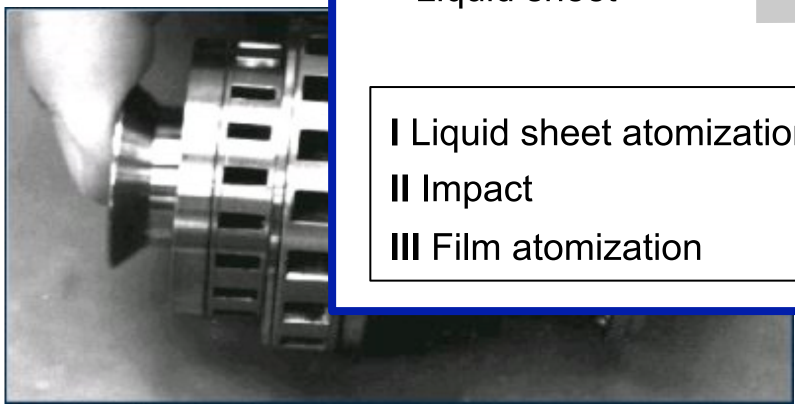
All images frmo theTLC project web site

Aeronautical injection systems:

LP injection system (R







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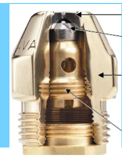
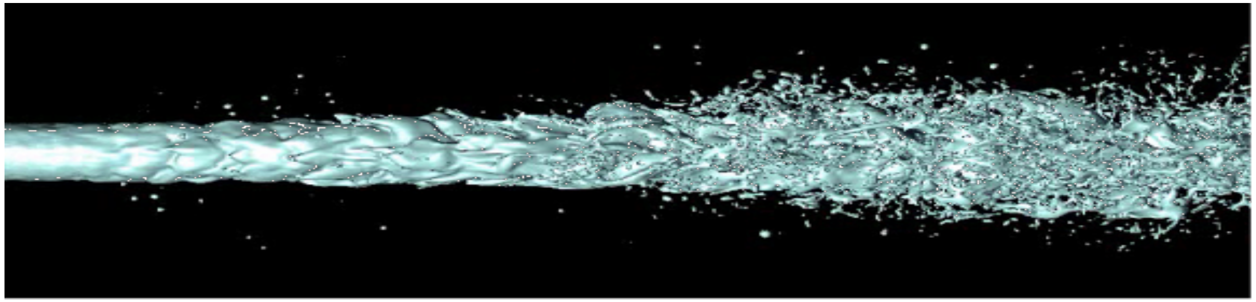
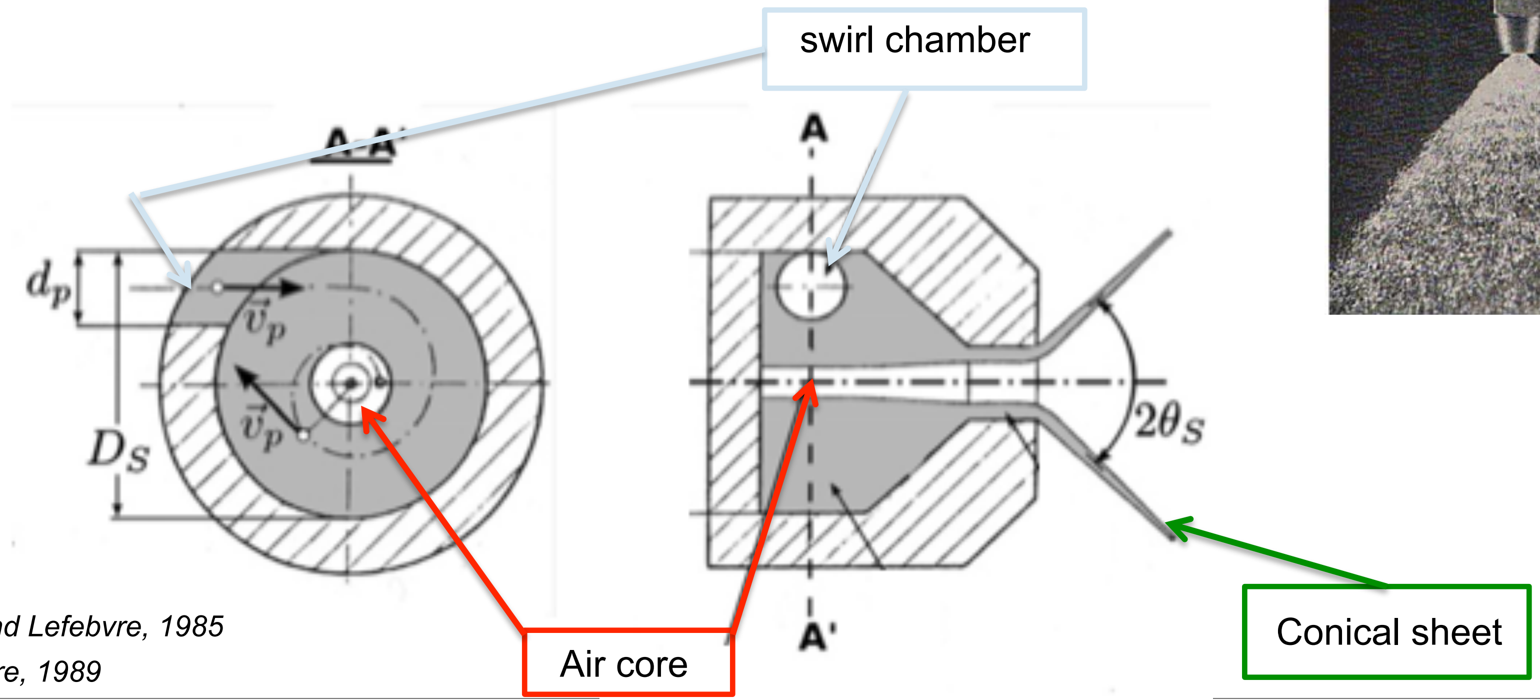


Liquid sheet atomization



Liquid jet surface and break-up near the jet nozzle *(Menard et al. Int. J. of multiphase flow, 33, 2007)*

Pressure swirl atomizer (simplex):

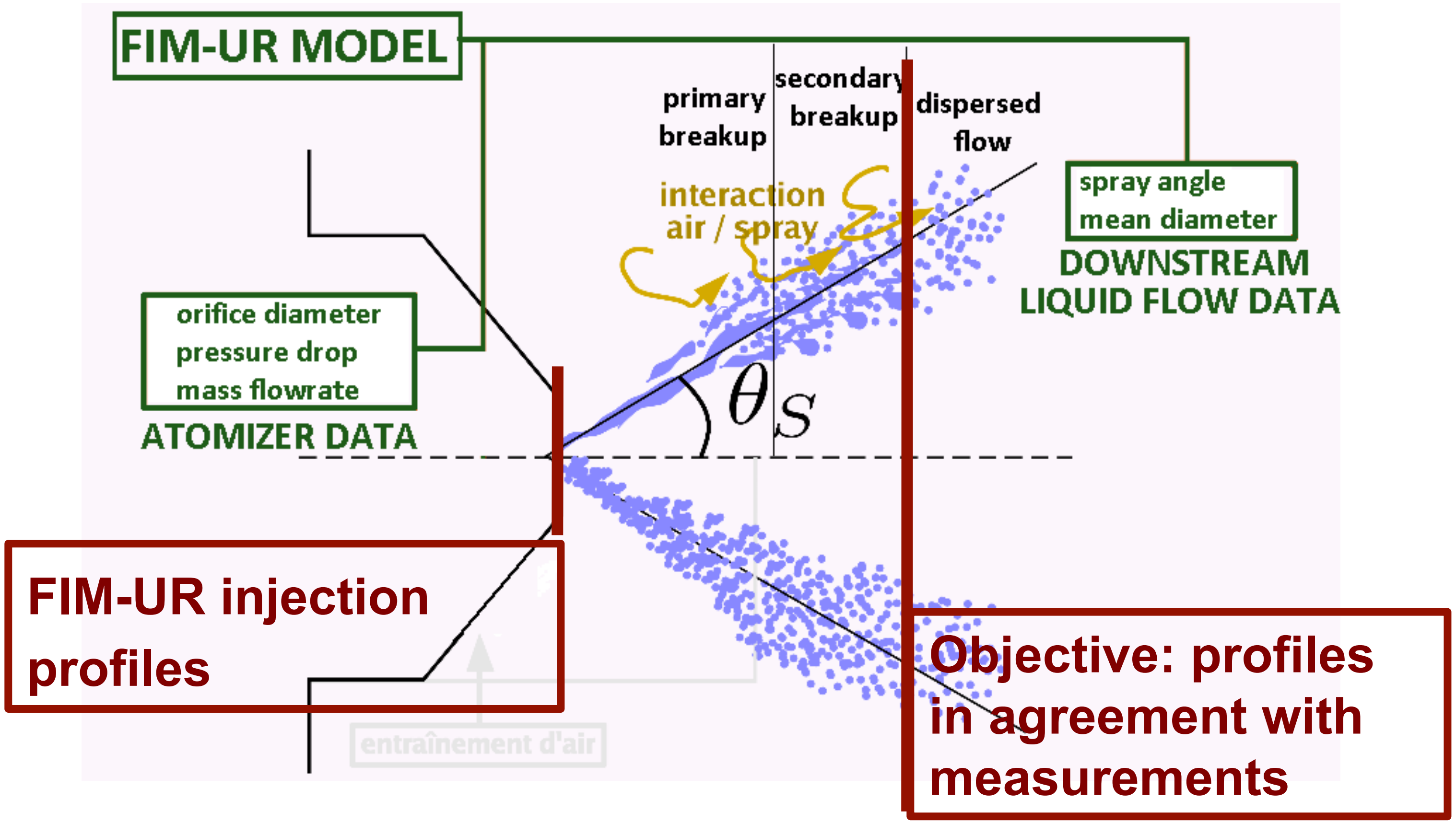


Risk and Lefebvre, 1985
Lefebvre, 1989

Fuel Injection Model by Upstream Reconstruction (FIM-UR model)

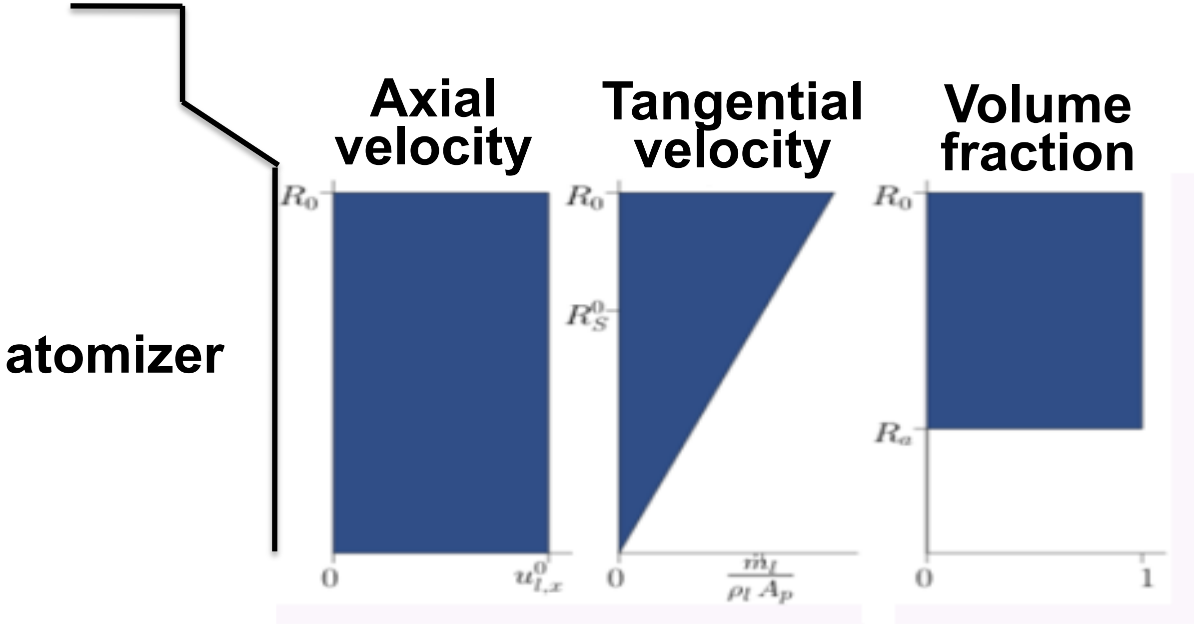
Sanjosé et al, IJMF 2010, Hannebique et al. FTAC 2013

Use atomizer data and flow characterisation to reconstruct inlet profiles at the injector tip to obtain physical profiles after secondary breakup (*Sanjosé et al, 2011)*



Fuel Injection Model by Upstream Reconstruction (FIM-UR model)

Resulting profiles at the injector outlet



Simple profiles linked to the:

- atomizer characteristics
- downstream spray data

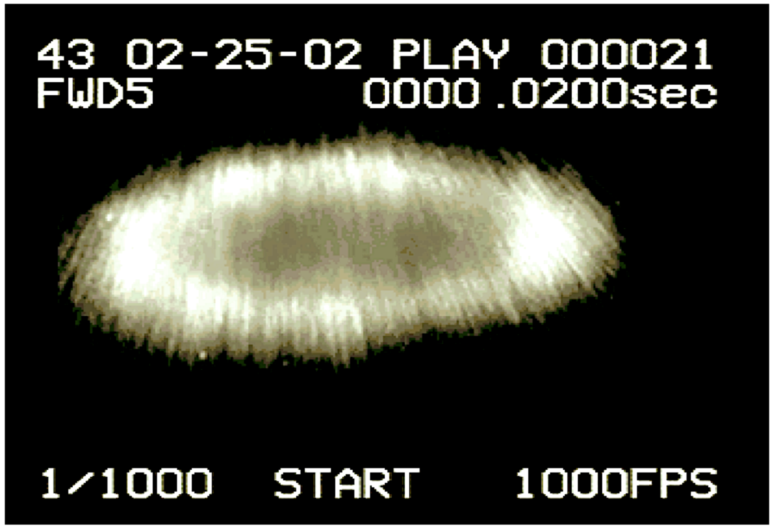
Validation

Experiment:

Yang et al., Pacific Symposium on Flow Visualization and Image Processing (2003)

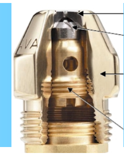
- Pressure swirl atomizer in ambient atmosphere
- Visualizations by fast cameras
- Measurements of velocity profiles and mean diameter for different operating points and different injectors

lateral view



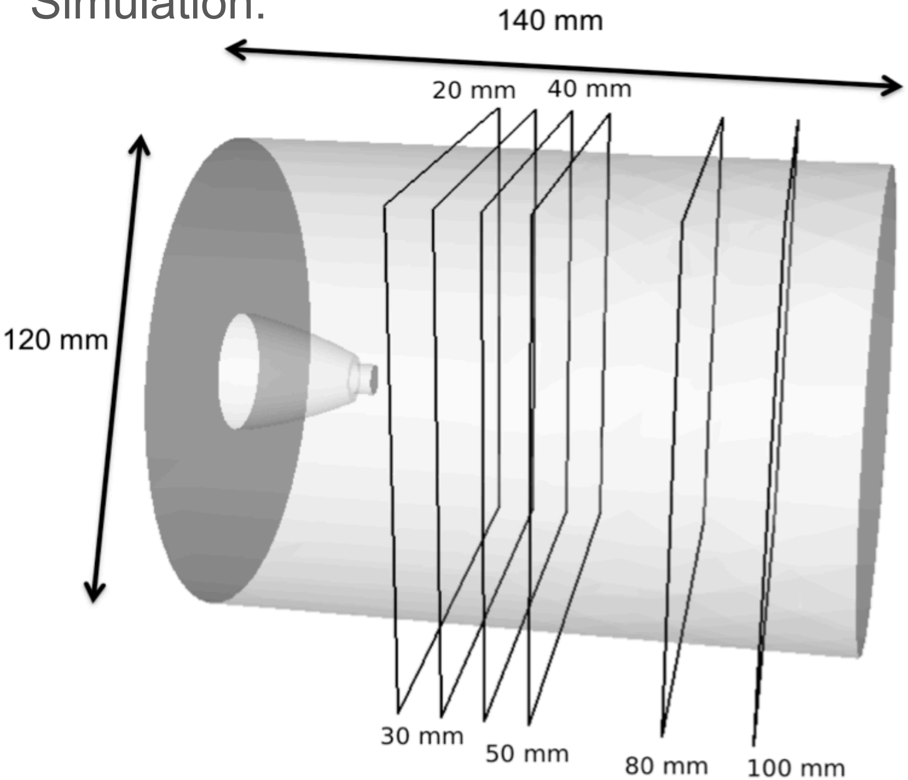
transverse view

Visualisation by fast cameras of the spray structure



Validation

Simulation:



Numerical domain and measurement planes

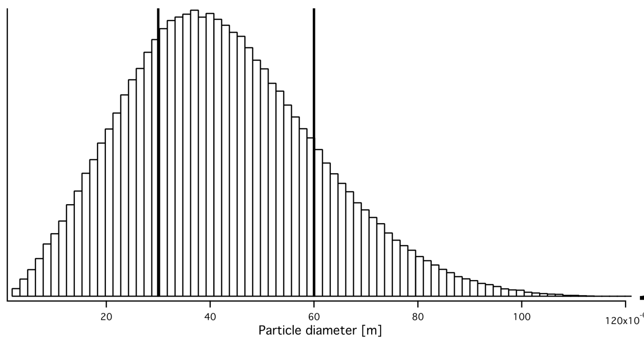
Atomizer characteristics

Injection diameter	0.5 mm
Discharge coefficient	0.93
Half spray angle	30°
SMD	60 µm
Liquid mass flow rate	3 g/s
Gas - liquid temperature	300 K

3D LES with AVBP

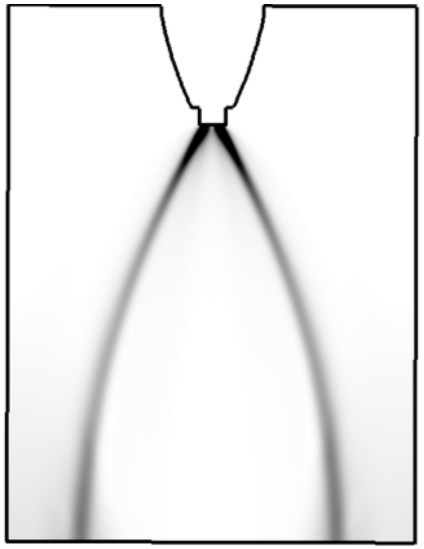
- WALE subgrid model *(Nicoud, 1999)*
- NSCBC Boundary conditions *(Poinsot et al, 1992)*
- Mesoscopic Euler & Lagrange

Drop size number distribution (Rosin-Rammler)

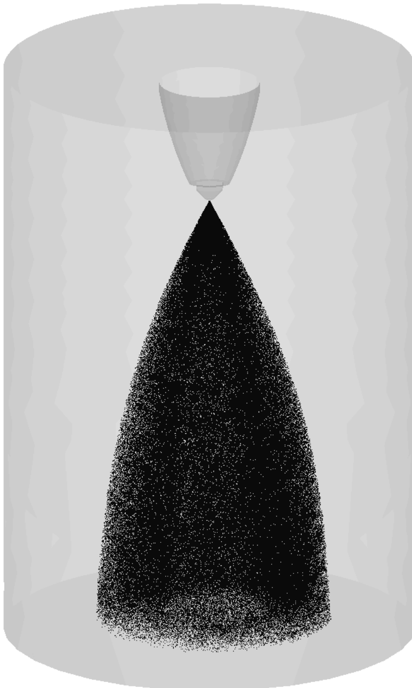


Validation

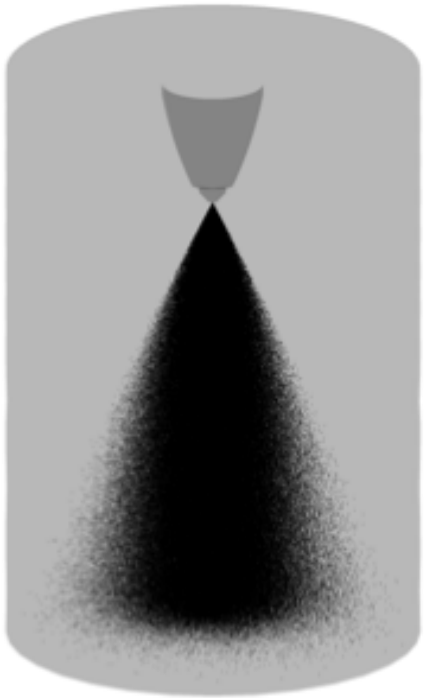
Results:



Eulerian



Lagrangian monodisperse



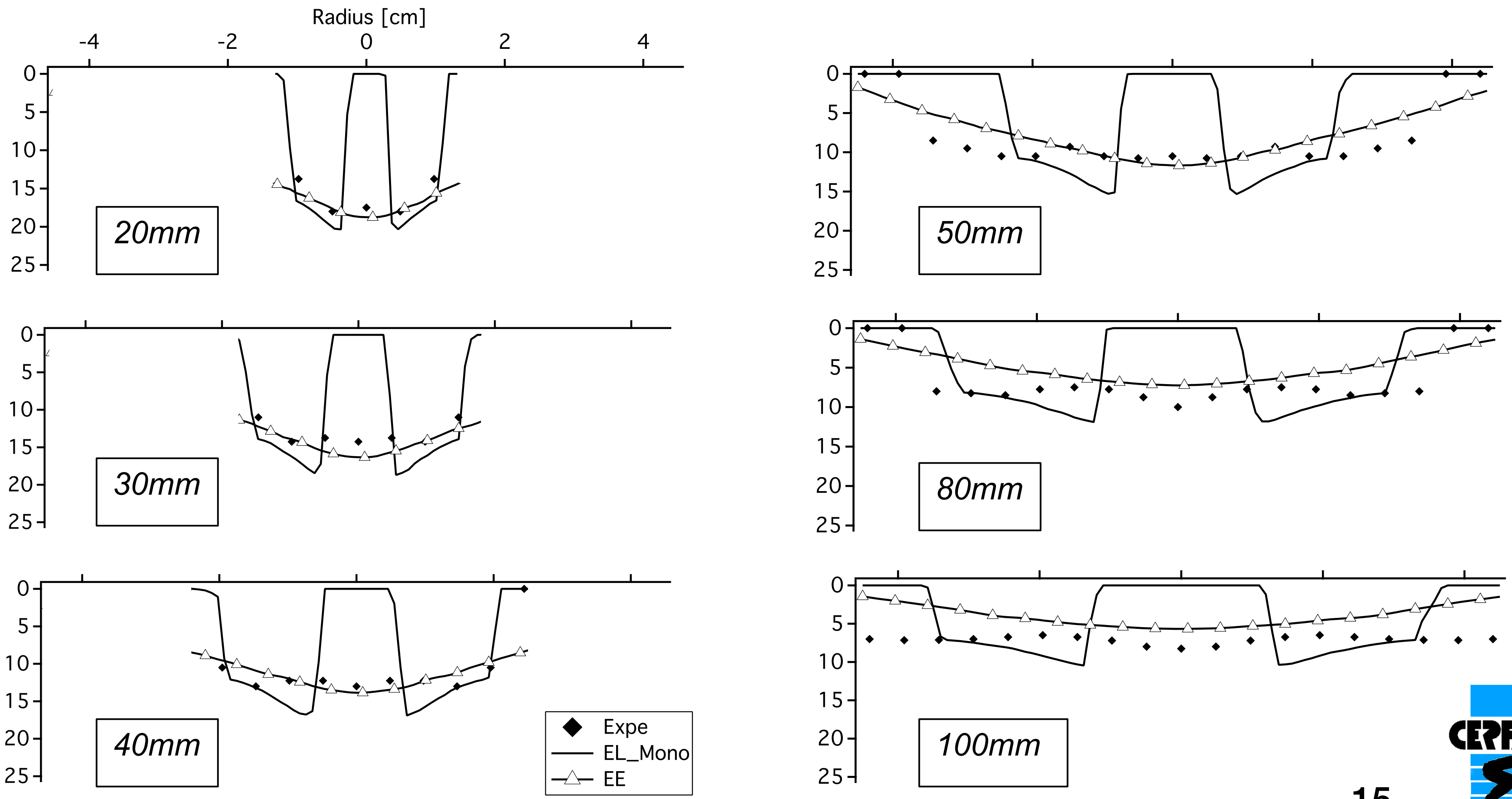
Lagrangian polydisperse

Spray angle and penetration well reproduced by all models

Validation

Results: Eulerian vs Lagragian (monodisperse)

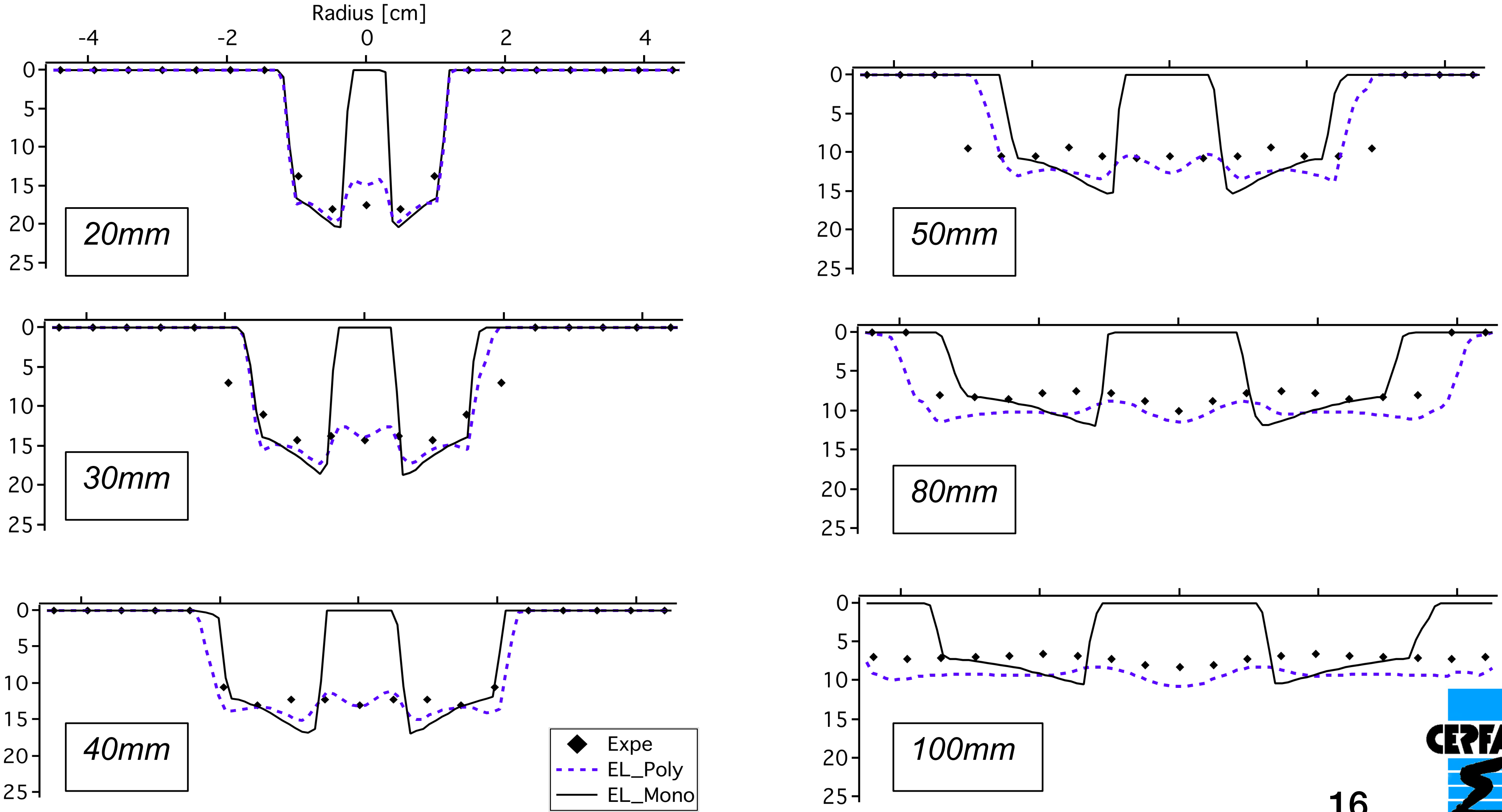
Liquid axial velocity

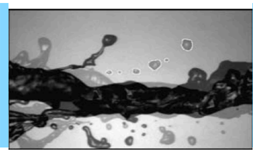


Validation

Results: Lagrangian, mono- vs polydisperse

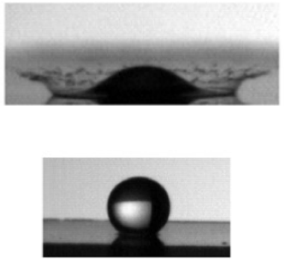
Liquid axial velocity



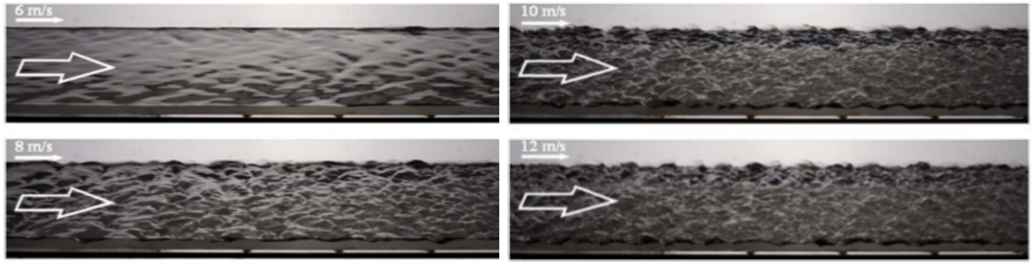


Liquid film formation and atomization

Chaussonnet et al., ILASS 2013



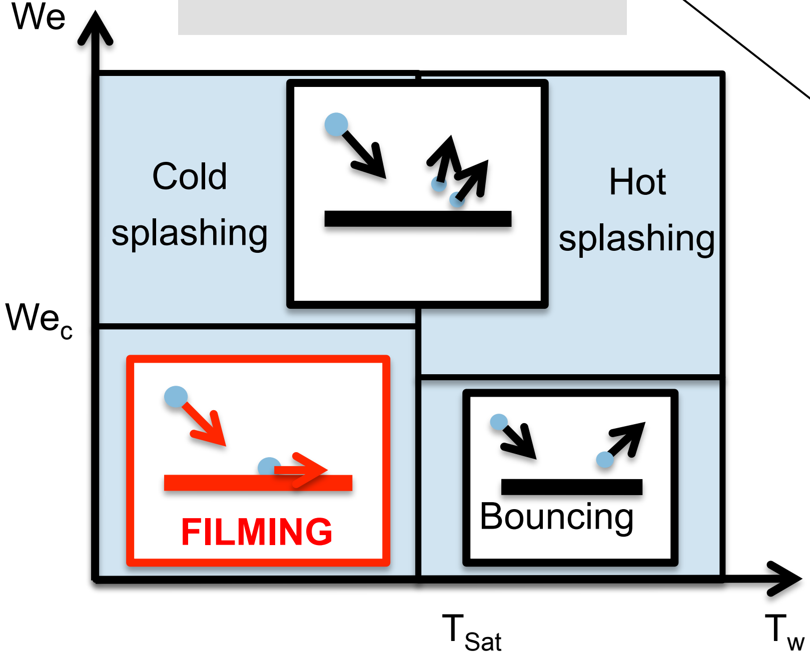
Moreira et al. PECS 2012

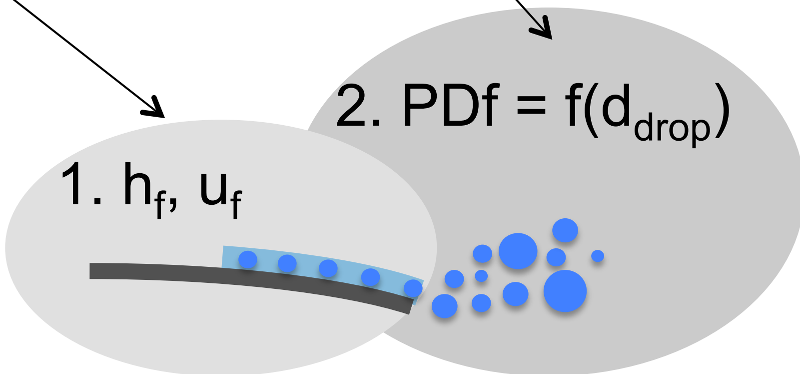


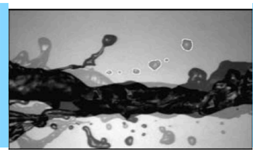
Hashmi et al., Proceedings of ASME Turbo Expo 2011

1. Film:
thickness h_f , velocity u_f

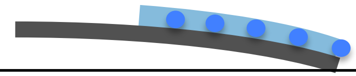
2. Spray:
drop size distribution





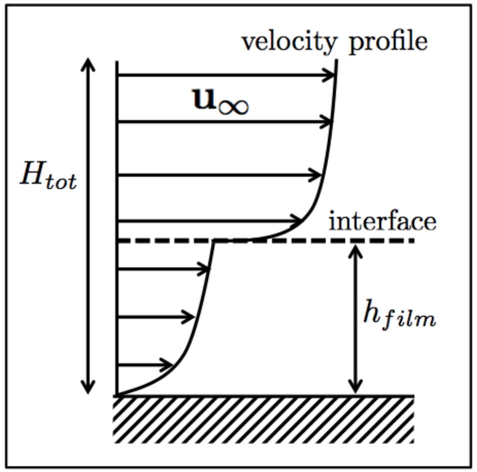


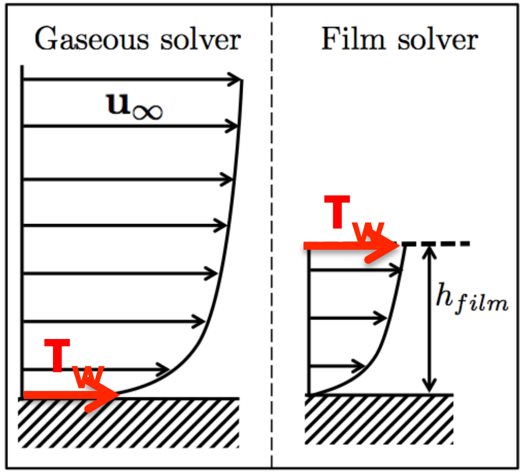
1. h_f, u_f



Liquid film formation : modelling

#	Assumption	Justification	Implication
1	Laminar flow	$\mathbf{Re = \frac{U_{film} h_{film}}{\nu_{film}} \sim \frac{1 \cdot 10^{-4}}{10^{-6}} = 100}$	No turbulence model
2	Incompressible	Liquid fuel	div u = 0
3	Quasi-static state	$\mathbf{\tau_{c,hydro} = \frac{h_{film}^2}{\nu_{film}} \sim 10^{-2}\ s}$	Parabolic profile
4	Thin film compared to longitudinal variations	$\mathbf{\frac{h_{film}}{H_{tot}} \sim \frac{1e^{-4}}{1e^{-2}} \sim 1\%}$	$\frac{\partial}{\partial T} << \frac{\partial}{\partial N}$





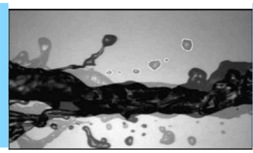
- Thin film:

⇒ VIRTUAL film

- Low interface velocity:

$$\mathbf{\frac{u_{interface}}{u_\infty} \sim \frac{u_{film}}{u_\infty} \sim 1\%}$$

⇒ Motionless boundary condition for gas: u=0



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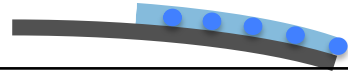

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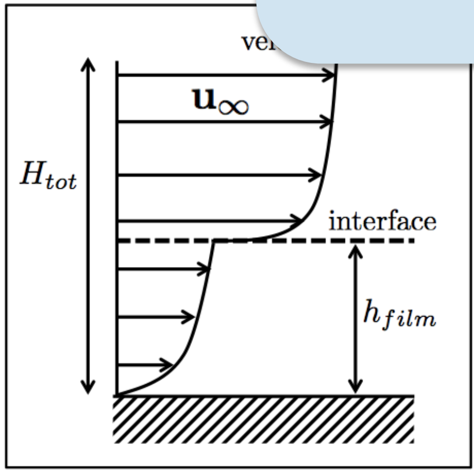
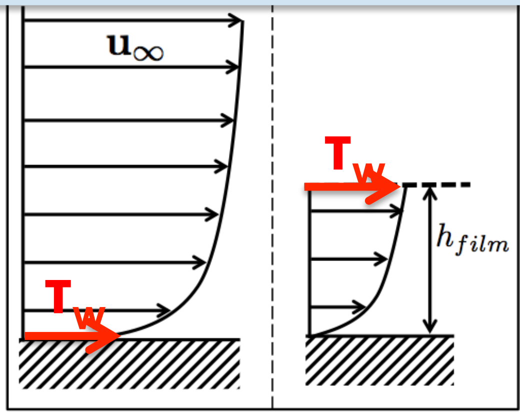
2	Incompressible	Liquid fuel	div u = 0
3	Quasi-sta		e
4	Thin film longitudi		N

$$\overline{u}_{film} = \frac{h_{film}}{2\mu_f} \cdot \tau_w - \frac{h_{film}^2}{3\mu_f} \cdot \frac{\partial p}{\partial x}$$





⇒ VIRTUAL film

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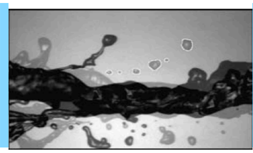
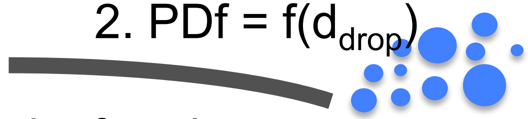
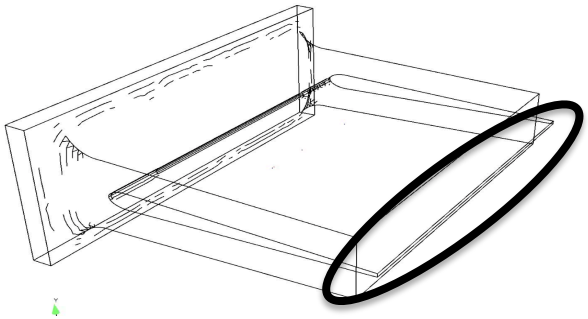


Fuel injection

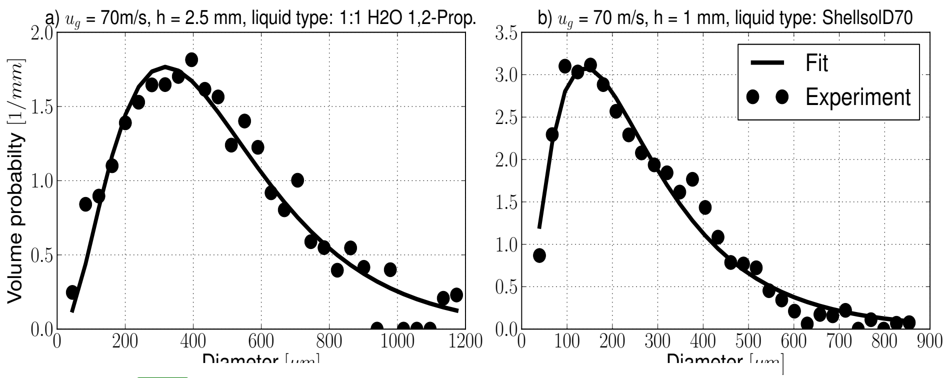


Liquid film atomization: primary break-up

Use available experimental data → Fit with a Rosin-Rammler function



Hong et al. 2002



$$f_3(d) = \frac{q\, d^{q+2}}{m^q} \exp\left[-\left(\frac{d}{m}\right)^q\right]$$

$$m = \frac{2\pi C}{u_g}\sqrt{6\,\alpha\, h\, \sigma}\left(\frac{1}{\sqrt{\rho_g}} + \frac{1}{\sqrt{\rho_l}}\right)\frac{\Gamma(2/q+1)}{\Gamma(3/q+1)}$$

$$q(\mathrm{We}, h) = \frac{\kappa}{\sqrt{\mathrm{We}}} + g(h) \quad \text{with} \quad g(h) = a\, h + b$$

Determination of 4 *unique* constants: ***C***, ***κ***, ***a*** and ***b**,* for the whole database:

- Different gas velocities (30 -> 70 m/s)
- 2 types of liquid: (Shellsol and 1:1 Water/Propanediol mix)
- 2 atomizing edge thicknesses: 1 and 2.5 mm

C [-]	κ [-]	a [1/m]	b [-]
0.1166	1.76	112	-0.043

Validation

The KIT-ITS experiment

Karlsruhe Institut of Technology-Institut für Thermische Strömungmaschinen

inlet: Air

Q=112 g/s

liquid injection

prefilmer

outlet

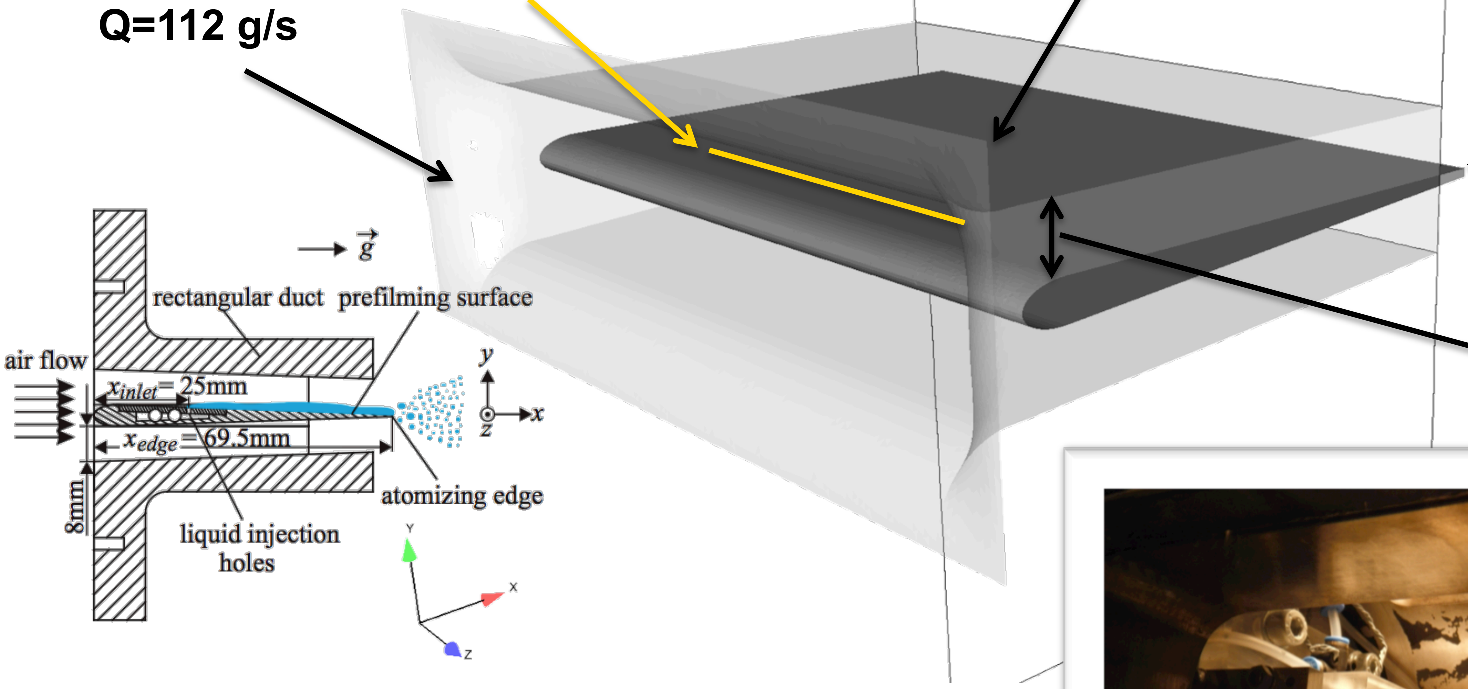
Atmosphere

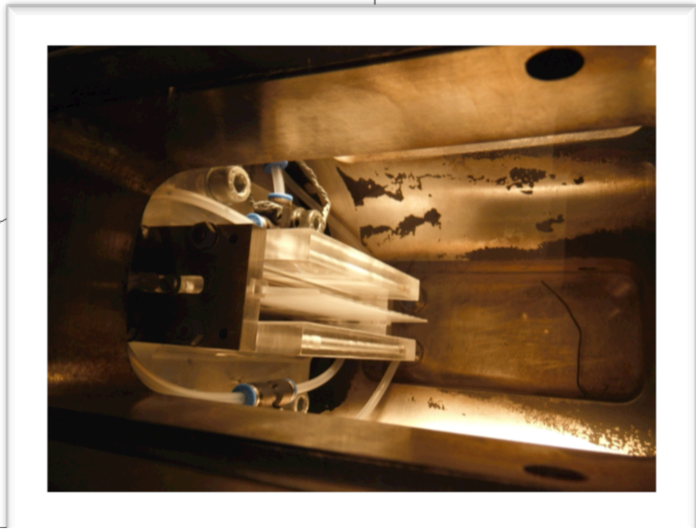
P=1 atm

atomizer

U_{gas} = 60 m/s

(on this section)

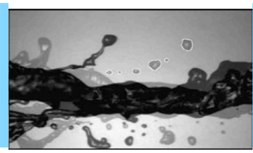




Gepperth et al., ILASS, 2010

Gepperth et al., ICLASS, 2012

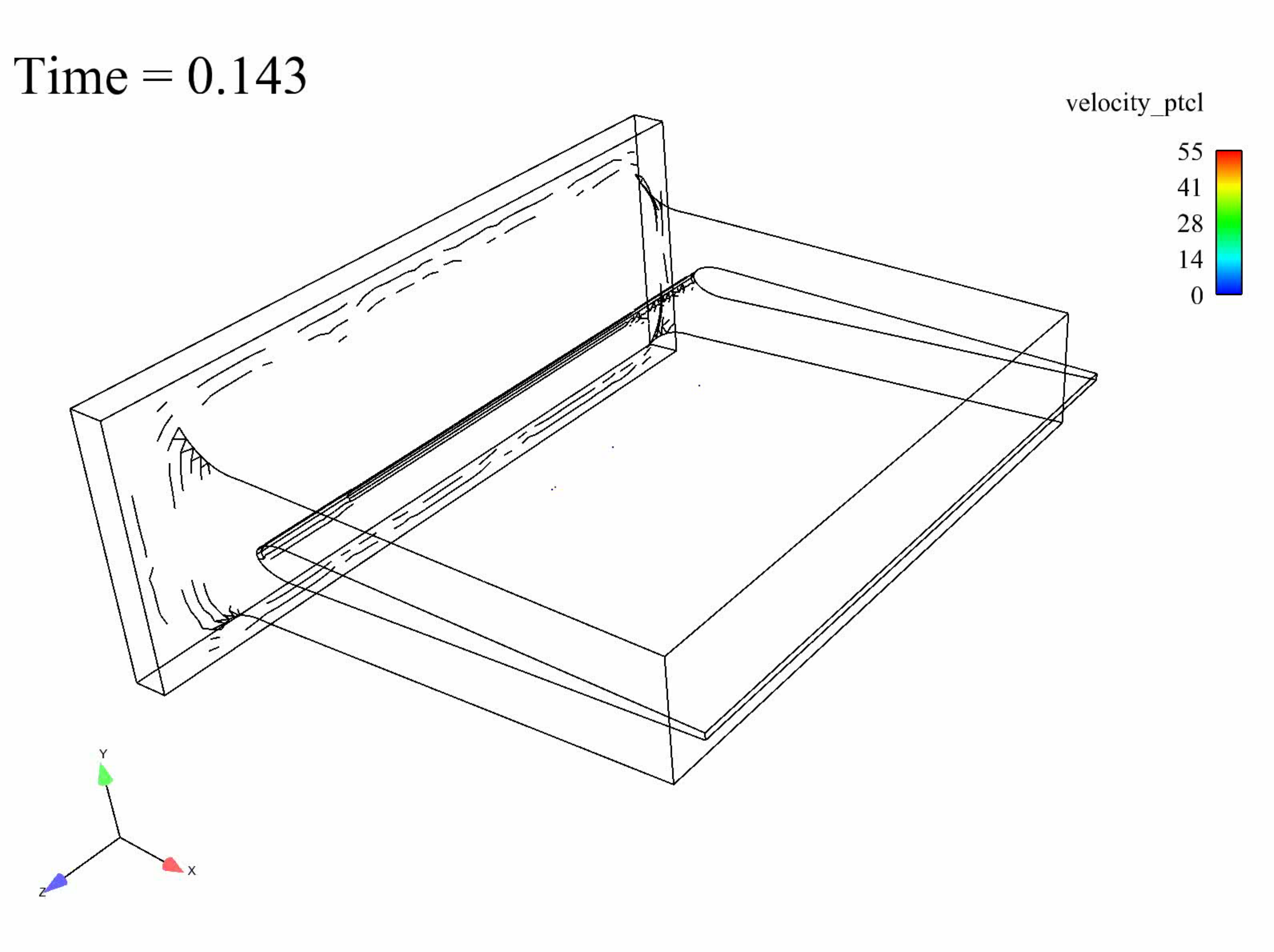
Gepperth et al., ASME, 2013



Validation

The KIT-ITS experiment

Karlsruhe Institut of Technology-Institut für Thermische Strömungmaschinen



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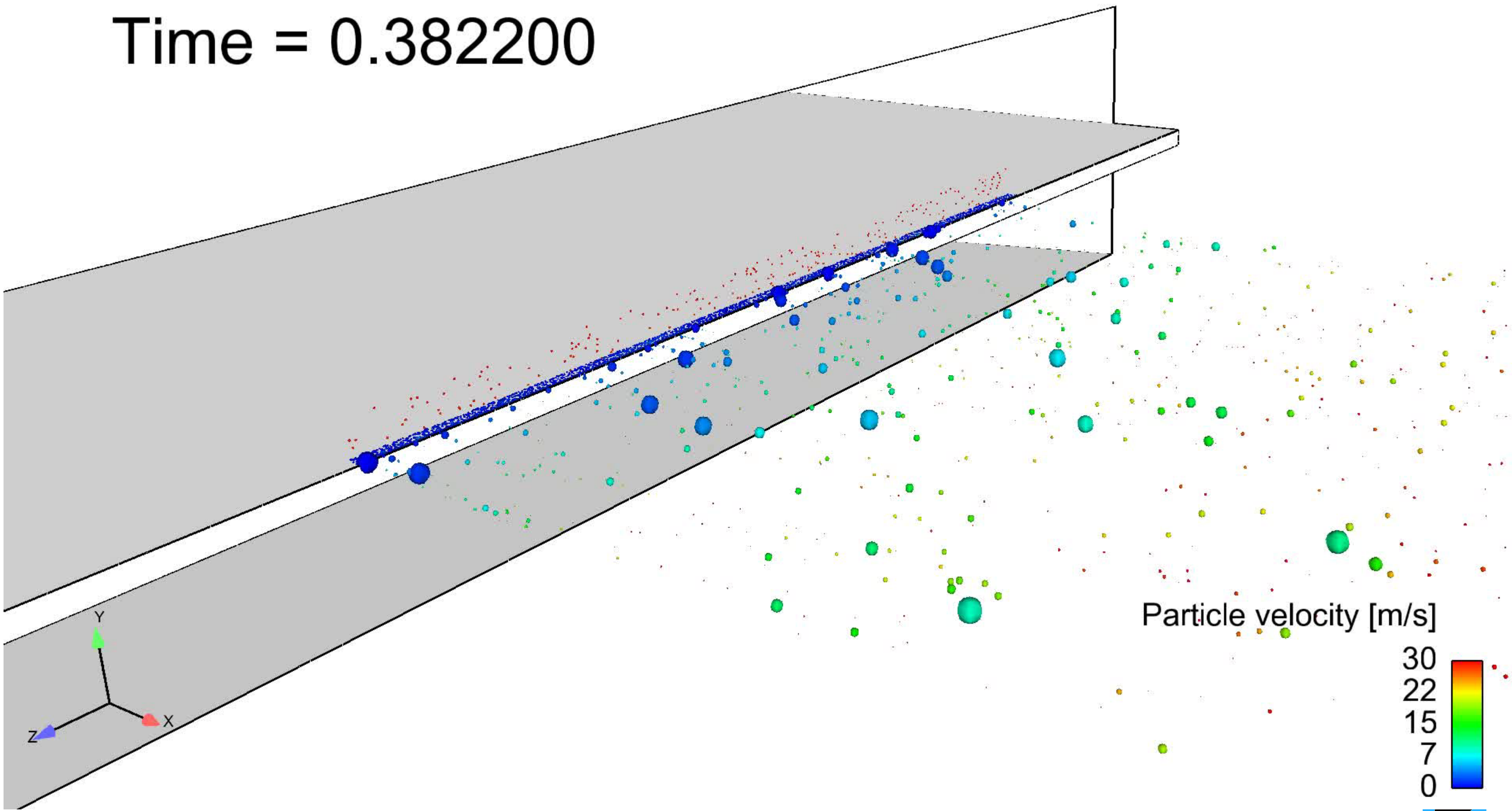

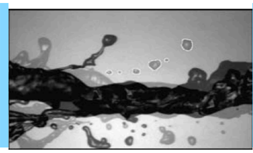

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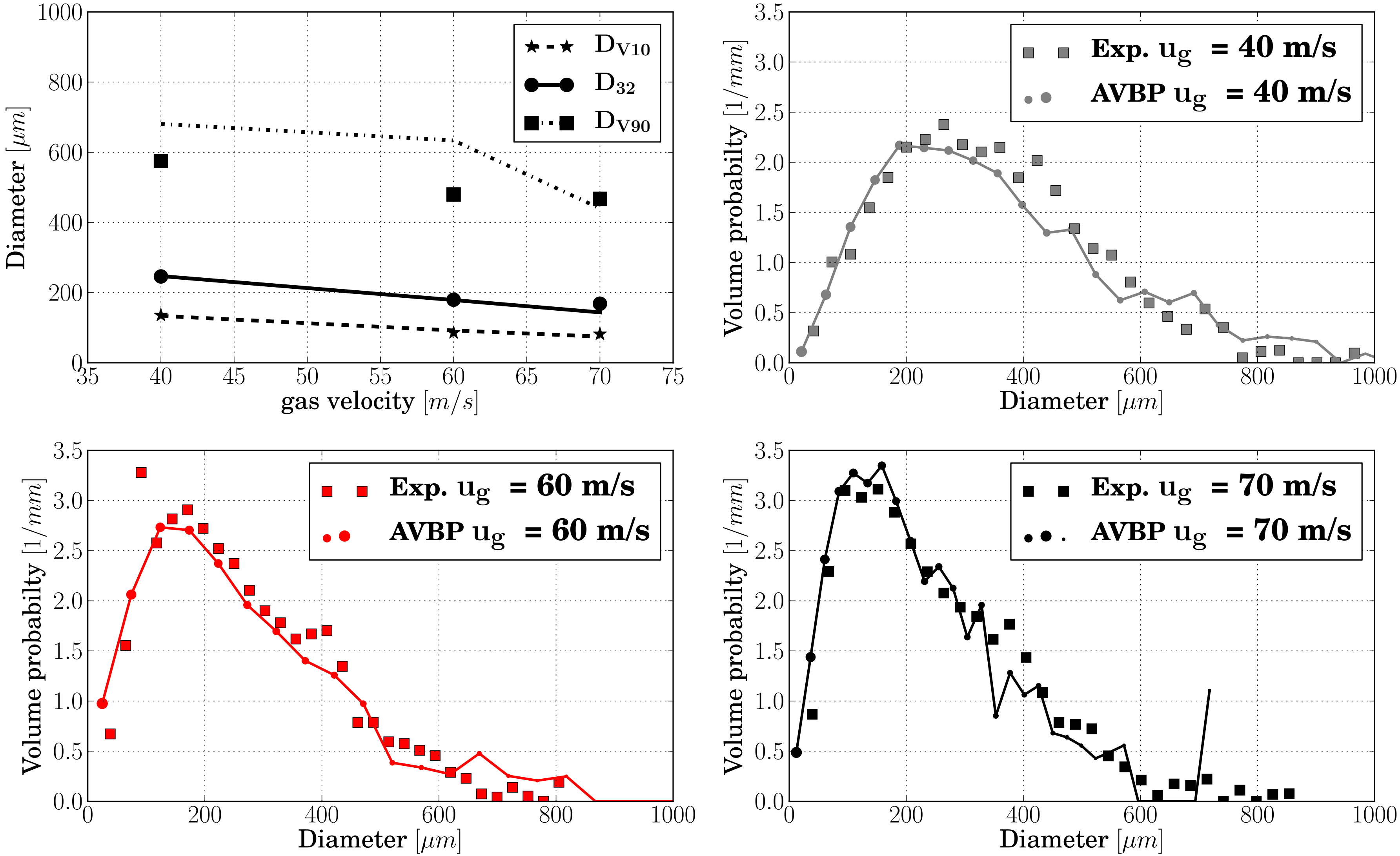
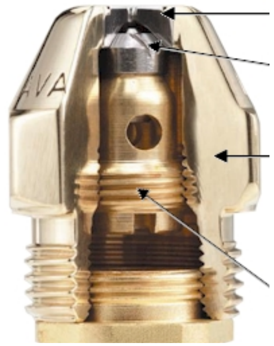
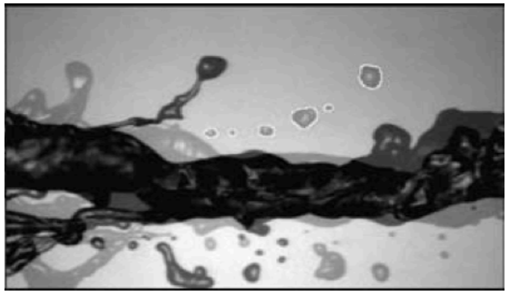


I - Modelling issues of two-phase combustion

- Eulerian formulation : Random Uncorrelated Motion
- Polydispersion
- Evaporation
- Fuel Injection



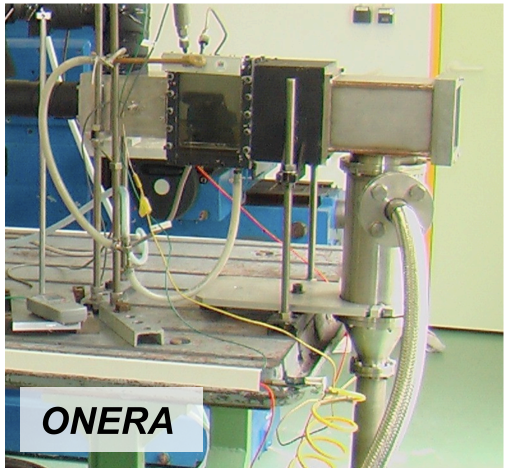


II – A lab-scale experiment

- Cambridge burner

III - Application to a complex geometry

- MERCATO burner



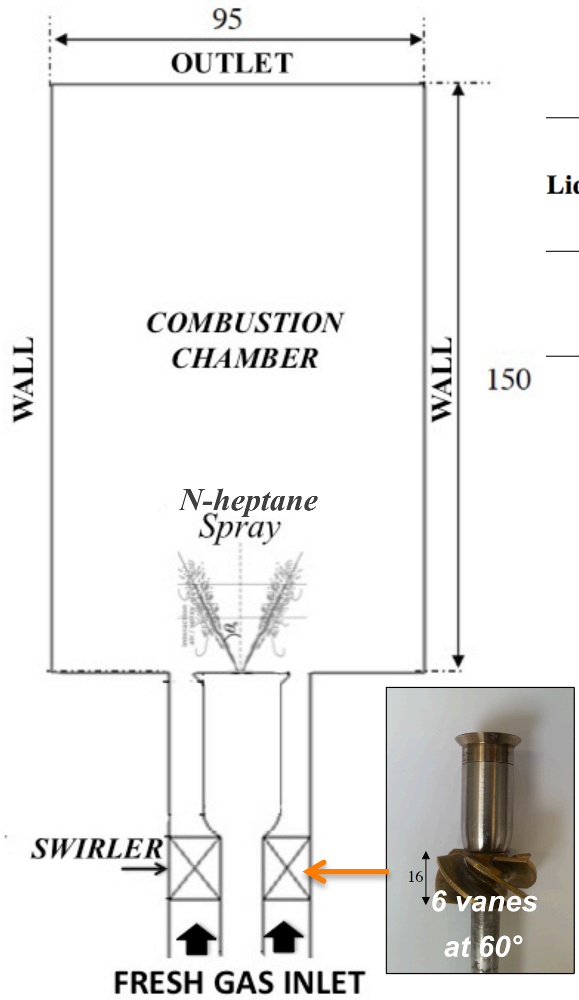
IV – Conclusions

Designed and operated by Cambridge university.

Cavaliere DE, Kariuki J and Mastorakos E (2013), Turbulence and Combustion, 91. pp. 347-372.

Tyliszczak A, Cavaliere DE and Mastorakos E (2013), Flow, Turbulence and Combustion, to appear.

Paulhiac et al., ILASS 2013

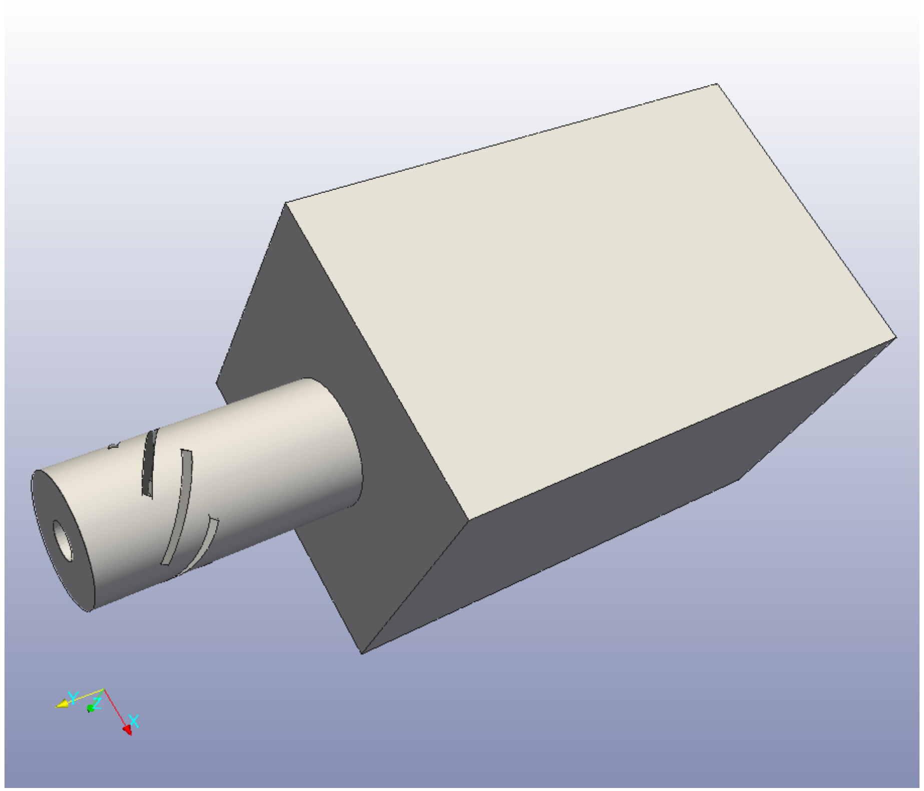


Operating conditions « SWH1 »

Liquid injection	Diameter of the injector	0.15 mm
	Angle of hollow cone	80°
	n-heptane flow-rate	0.12 g/s
	Sauter Mean Diameter	40 µm
Air Inlet	Air flow-rate	500 L/s
	Temperature	298 K
	Pressure	1 bar
	Global equivalence ratio	0.042

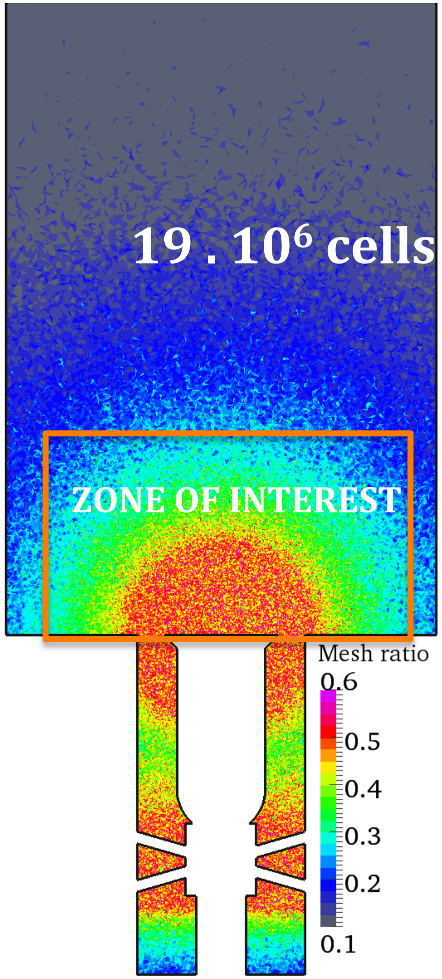
- ✓ **Velocity measurements**
- ✓ **Flame position (OH* chemiluminescence and OH-PLIF)**
- ✓ **Spray position (MIE-scattering)**
- **Liquid droplet speed and diameter**
- **Wall temperatures**

GEOMETRY



- 2-steps heptane chemistry
- Lagrangian approach
- FIMUR injection
- Polydisperse spray

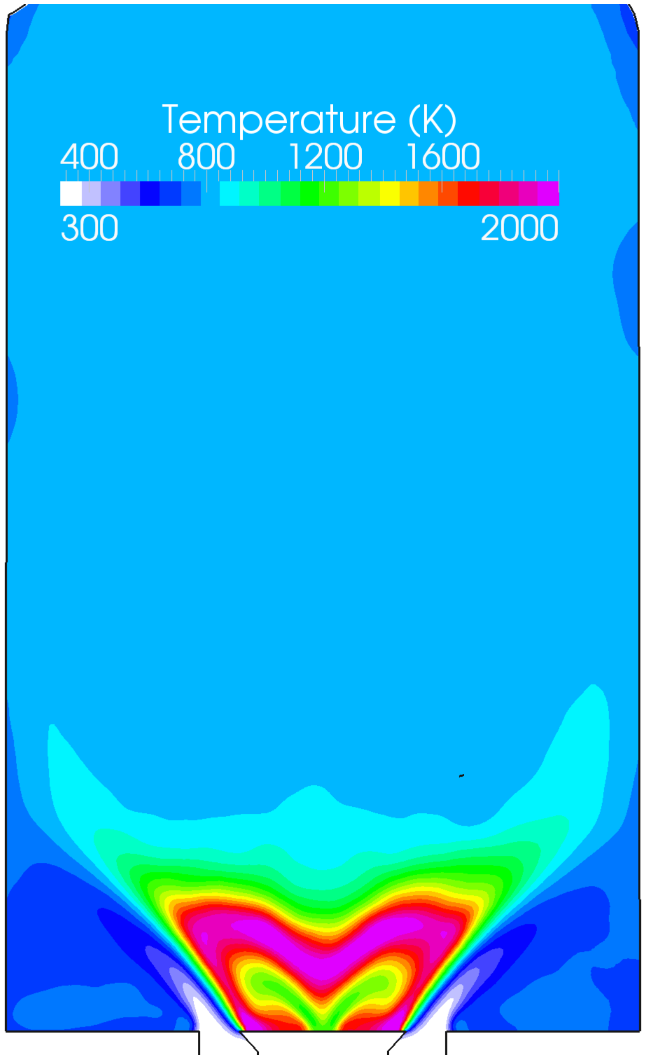
MESH



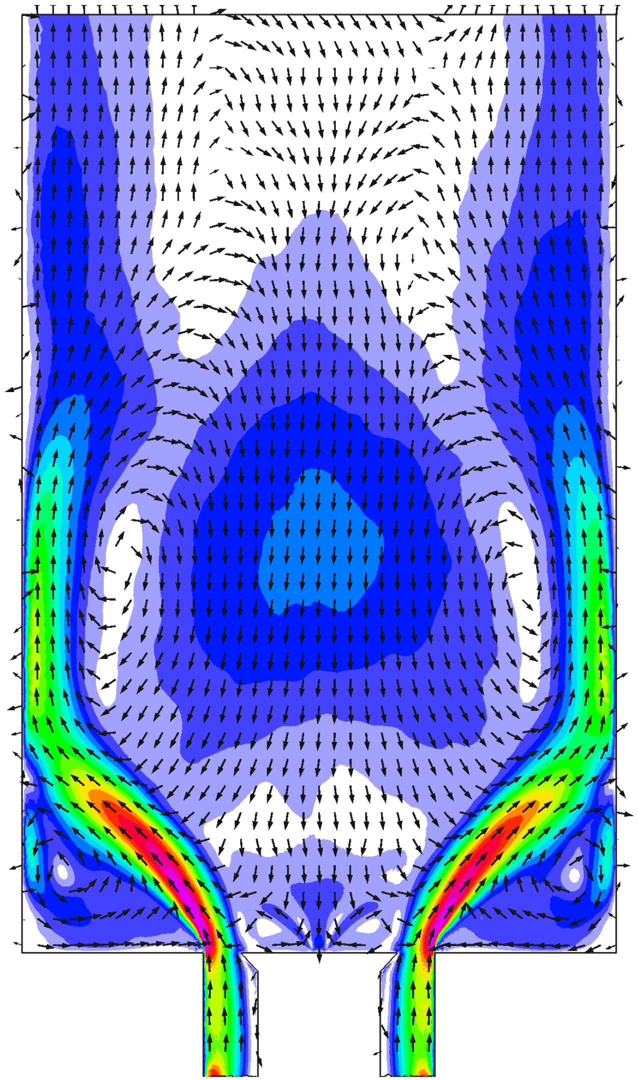
Results

MEAN FIELDS

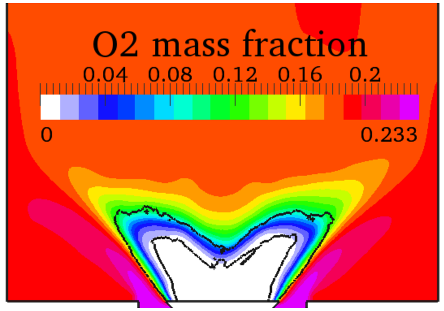
Diffusion flame

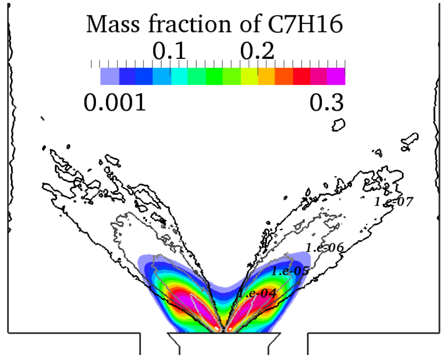


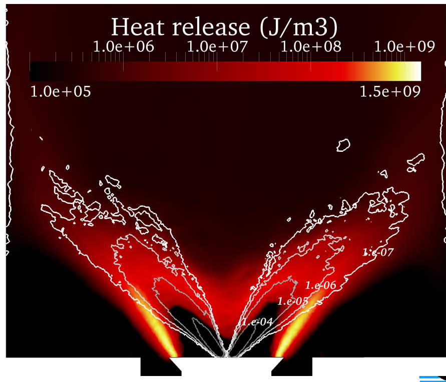
Gas Temperature



Gas axial velocity

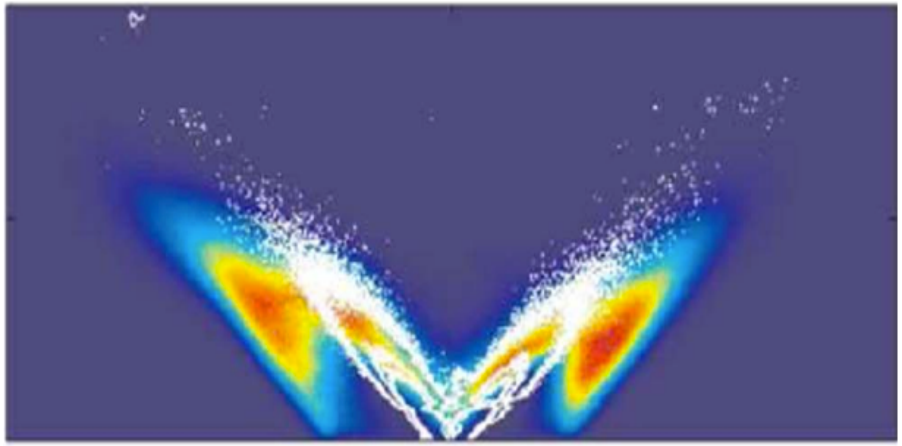




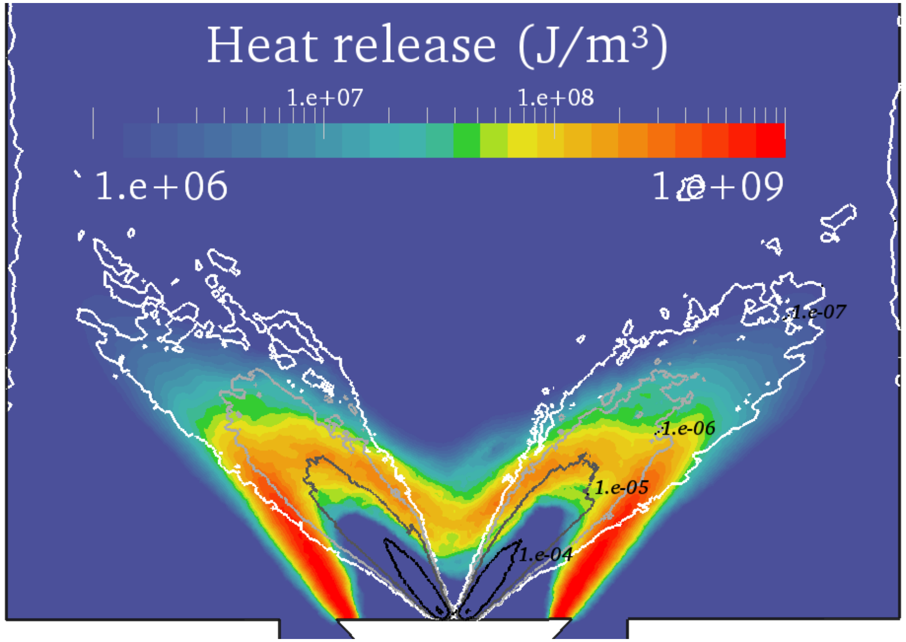


Results — Qualitative comparison with experiment

MIE scattering (spray)
+ OH-PLIF (reaction zone)

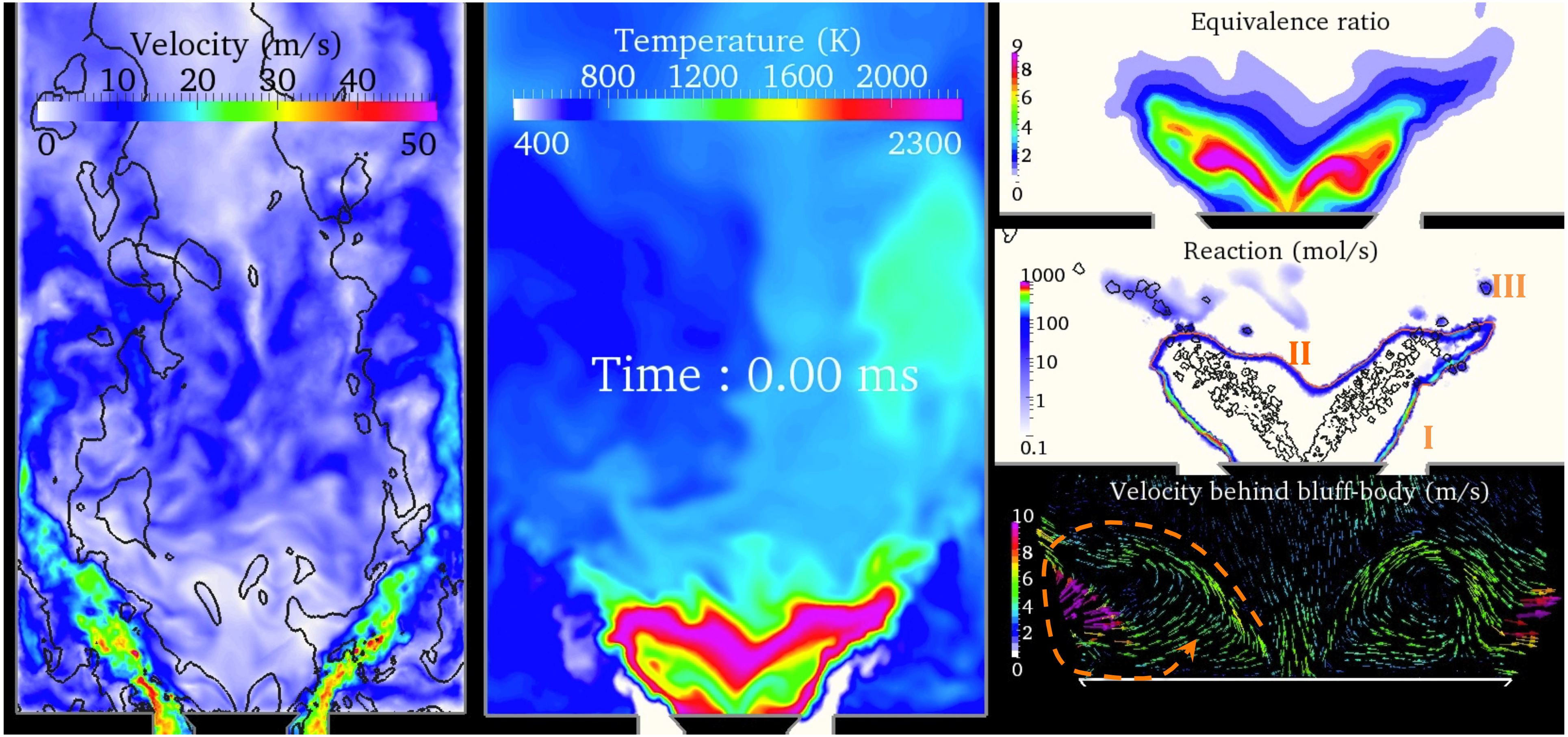


Simulation



Results

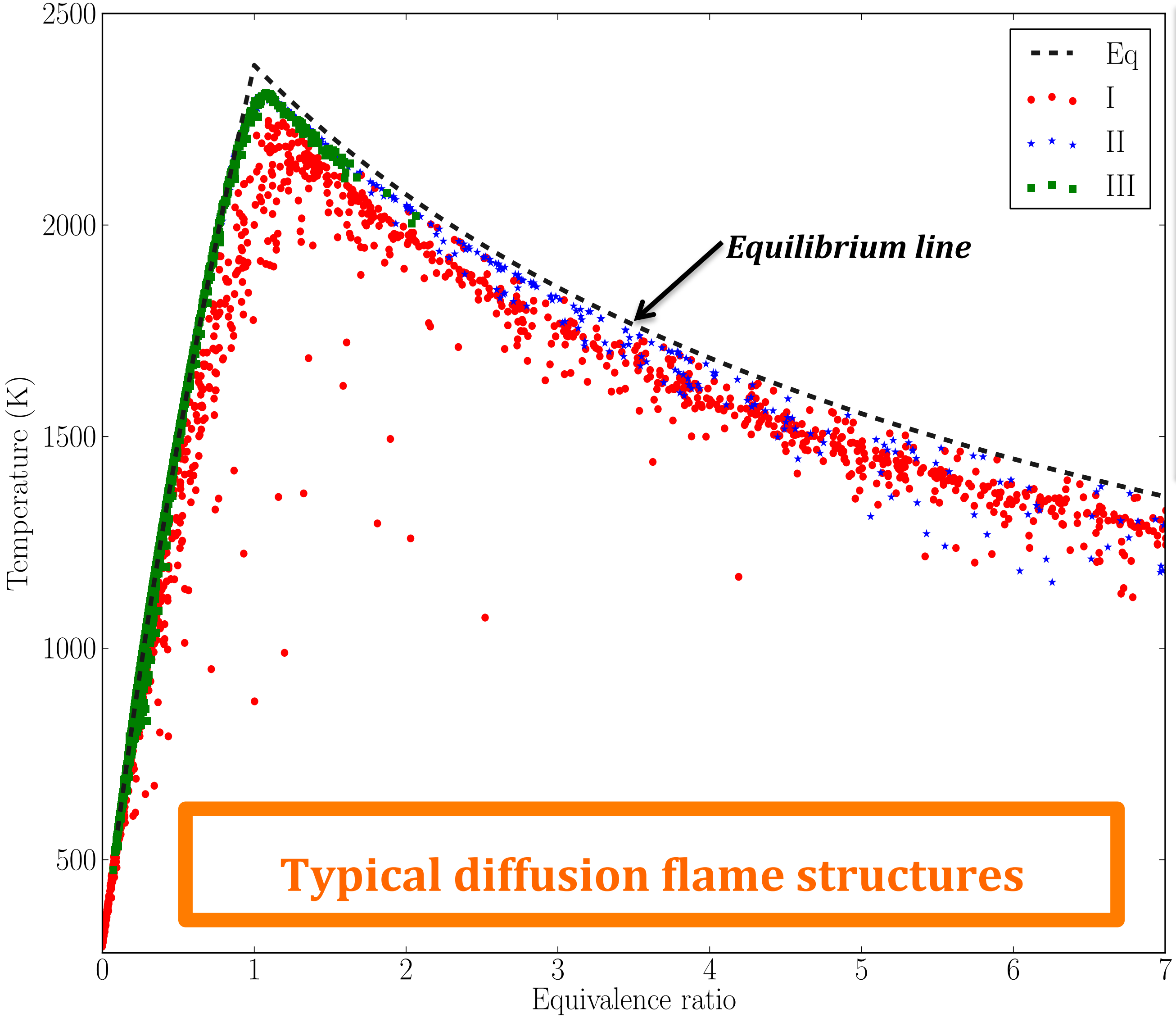
Instantaneous fields



A lab-scale experiment

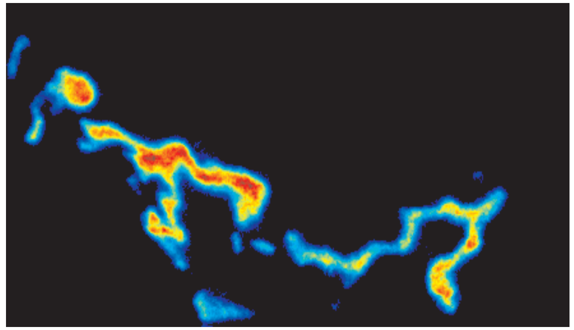
Results

Instantaneous fields



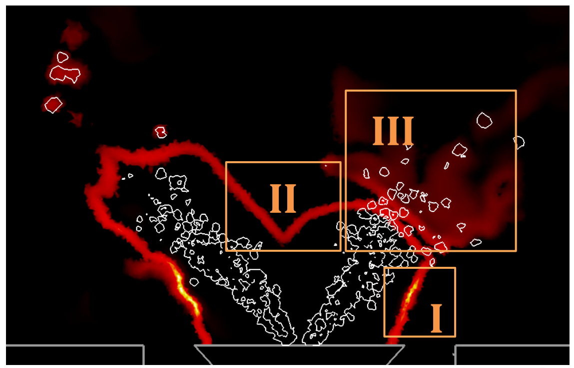
EXP.

Instantaneous OH-PLIF



SIM.

Reaction rate



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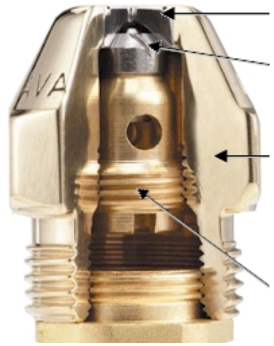

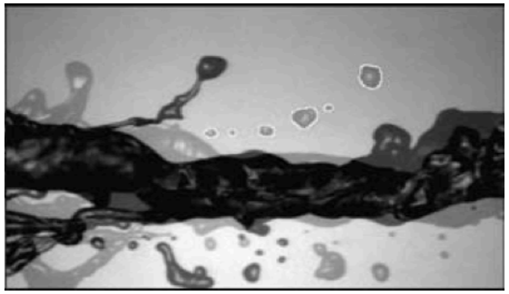

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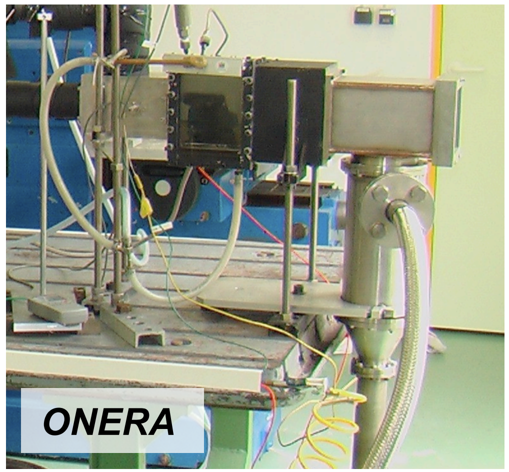
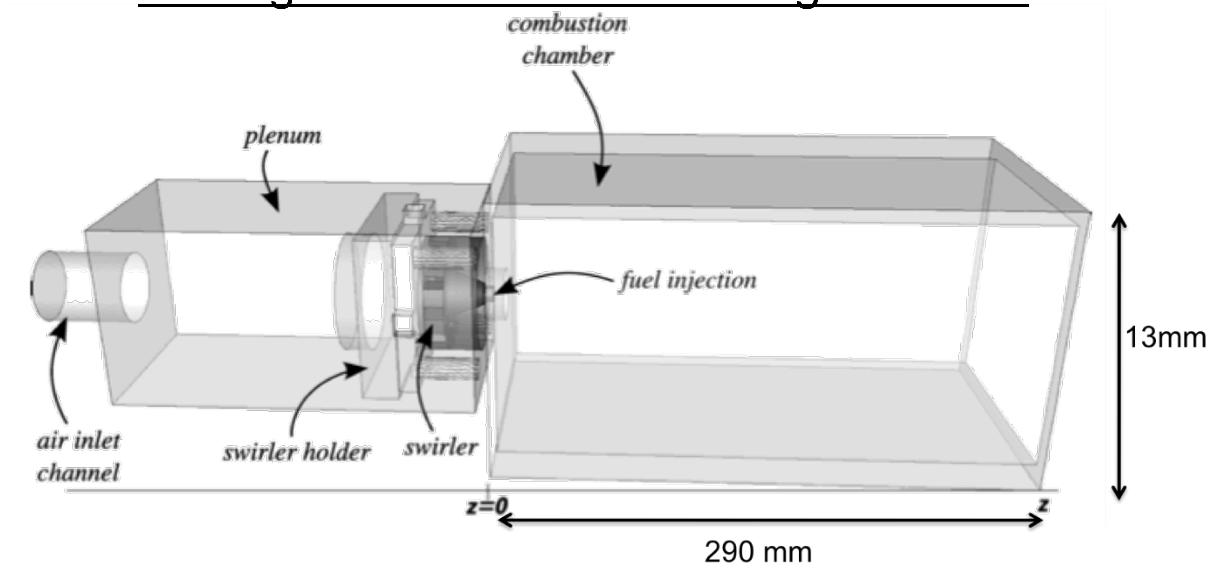
- MERCATO burner

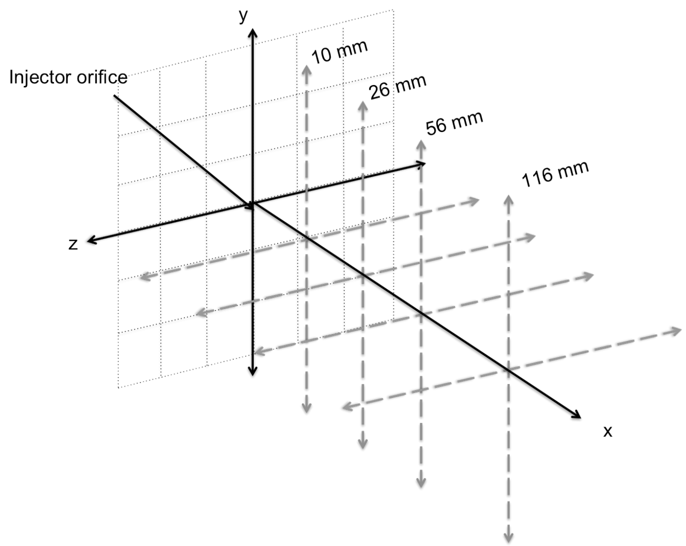


IV – Conclusions

Test-rig located at ONERA Fauga Mauzac



Operating point:	
Air mass flow rate	35,5 g/s
Liquid mass flow rate	2,26 g/s
Pressure	1 atm
Gas - Liq temperature	285 K
Eq. ratio	0.95



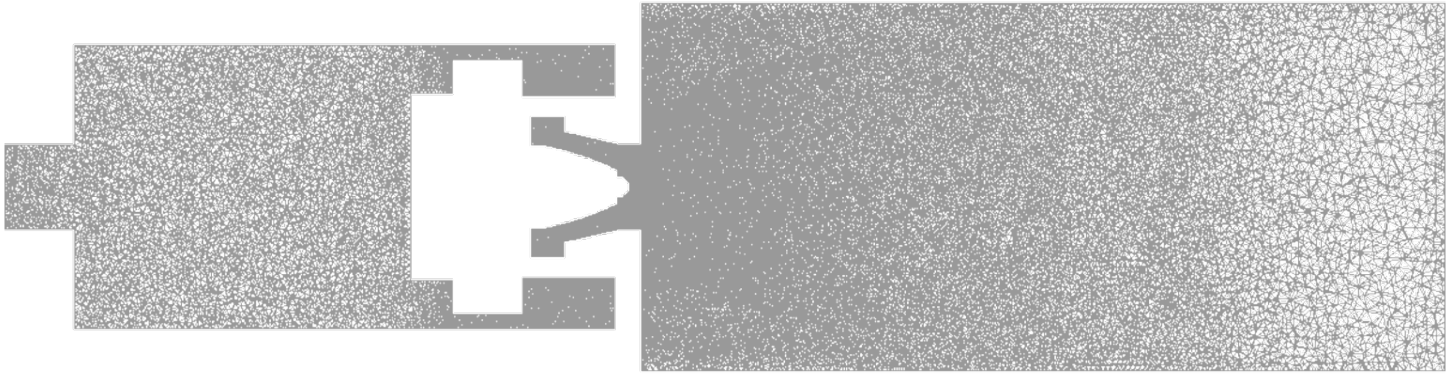
Measurements of stationary combustion:

Lecourt 2009

- ✓ Axial velocities for gas/liquid phases (PIV)
- ✓ Flame visualisation

Numerical set-up

Hannebique 2013 (PhD)



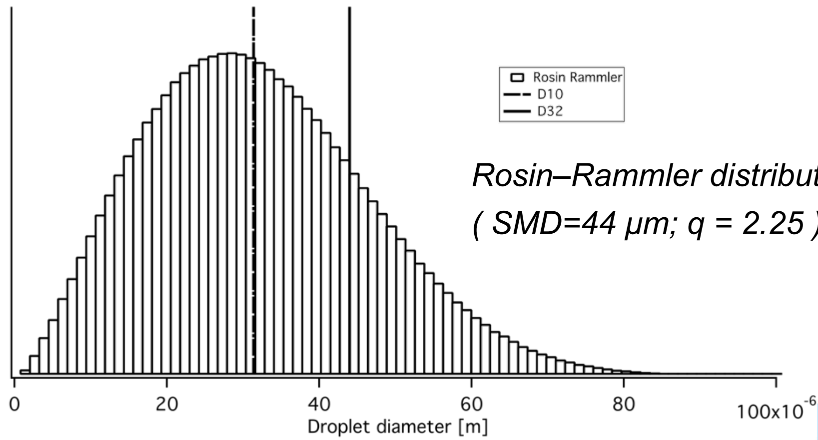
Mesh in the median cut plane (2 000 000 nodes)

- **2-steps kerosene chemistry**
- **Lagrangian approach**
- **FIMUR injection (half spray angle 40°, diameter 0.5 mm)**

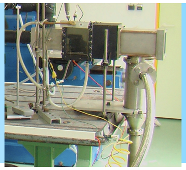
ELD10: Monodisperse D_{10}=32μm

ELD32: Monodisperse D_{32}=SMD=44 μm

ELRR: Polydisperse



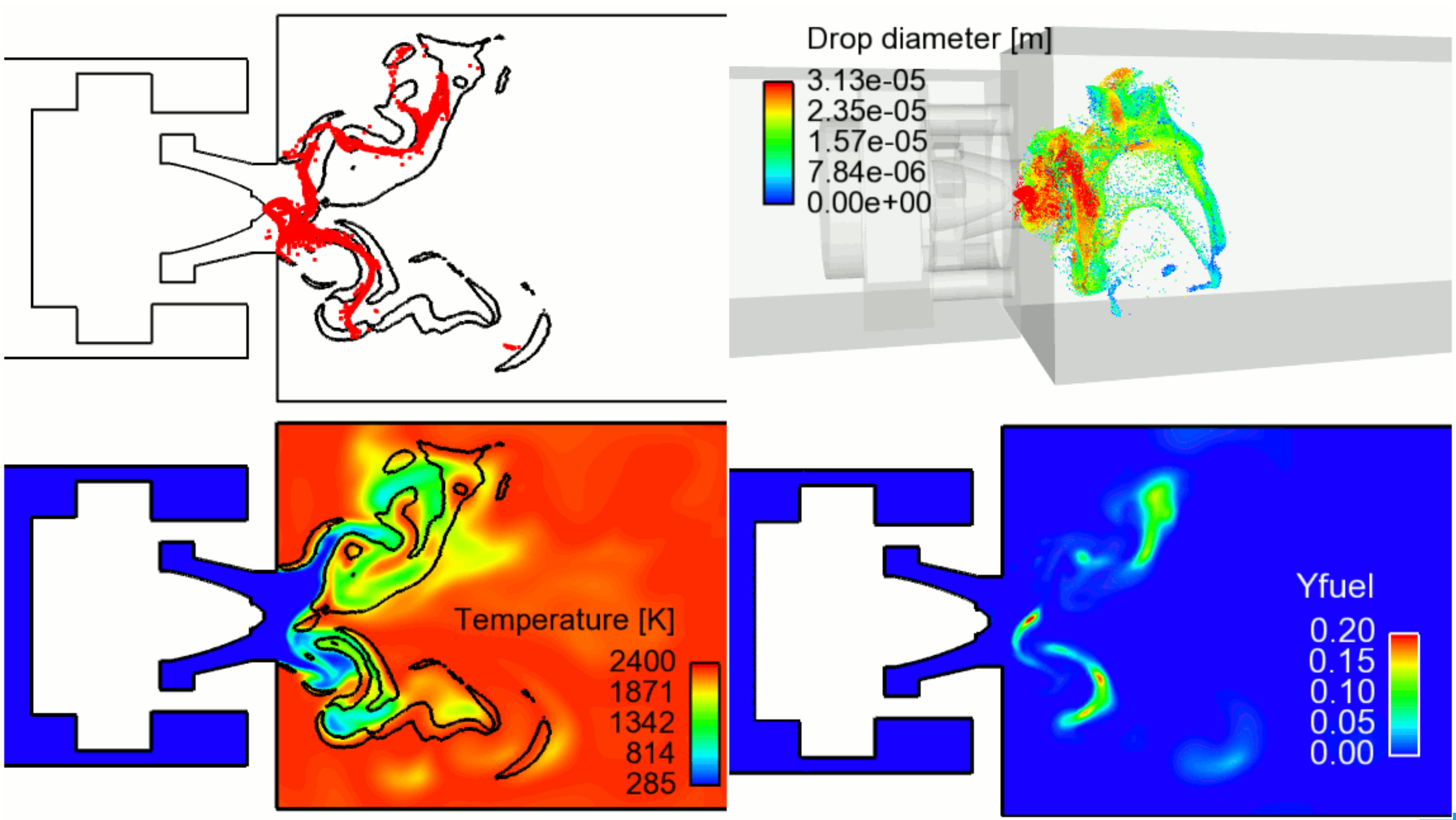
Rosin–Rammler distribution
(SMD=44 μm; q = 2.25)



Application to MERCATO

Droplets and Heat release isoline

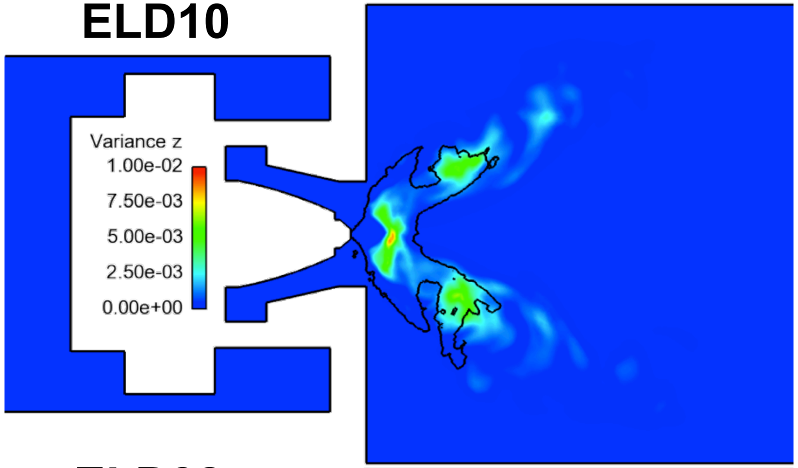
Drop diameter



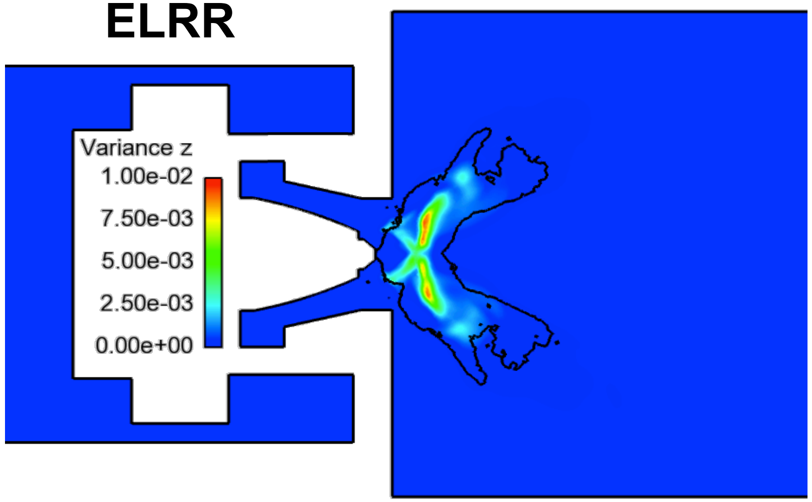
Gaseous temperature

Kerosene vapor

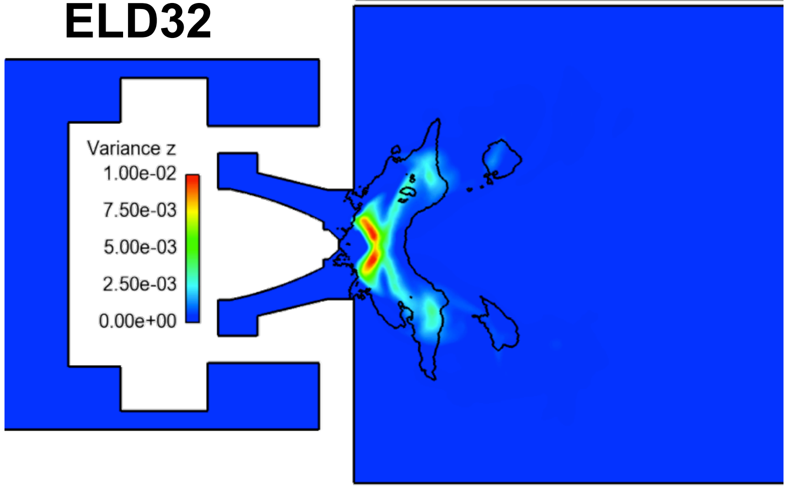
ELD10



ELRR



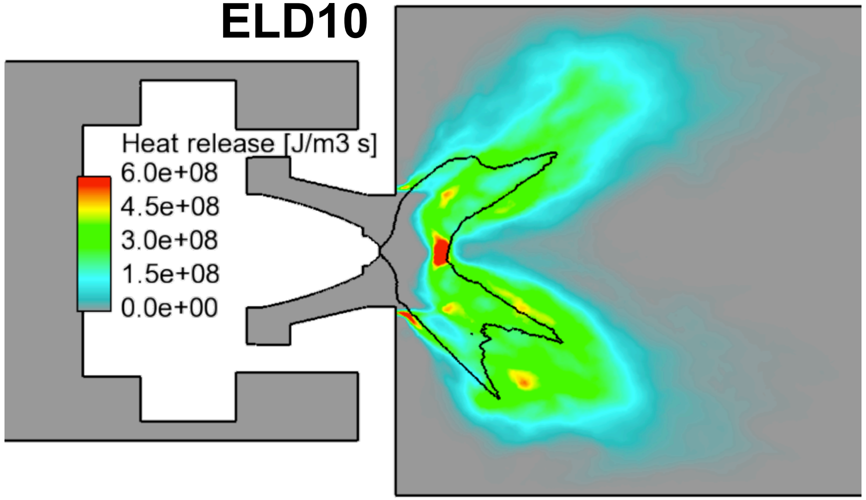
ELD32



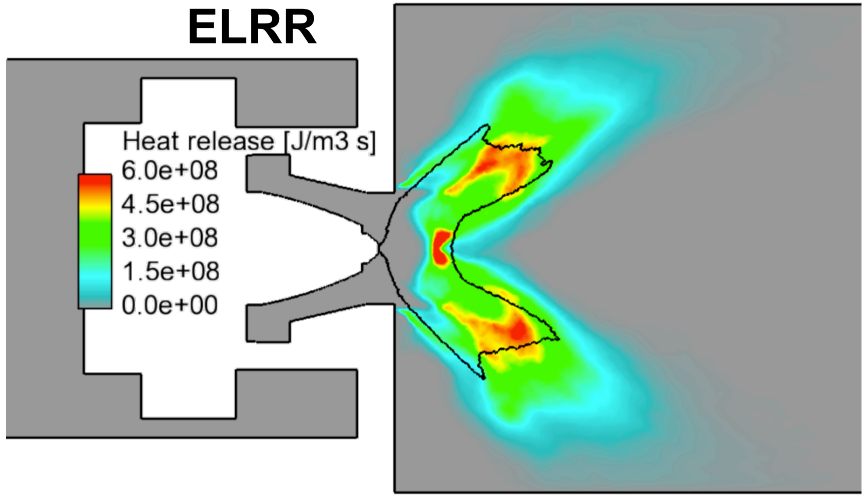
Mixture fraction variance field in the median cut plane with liquid volume fraction isoline ($\alpha_l = 10^{-4}$)

Application to MERCATO

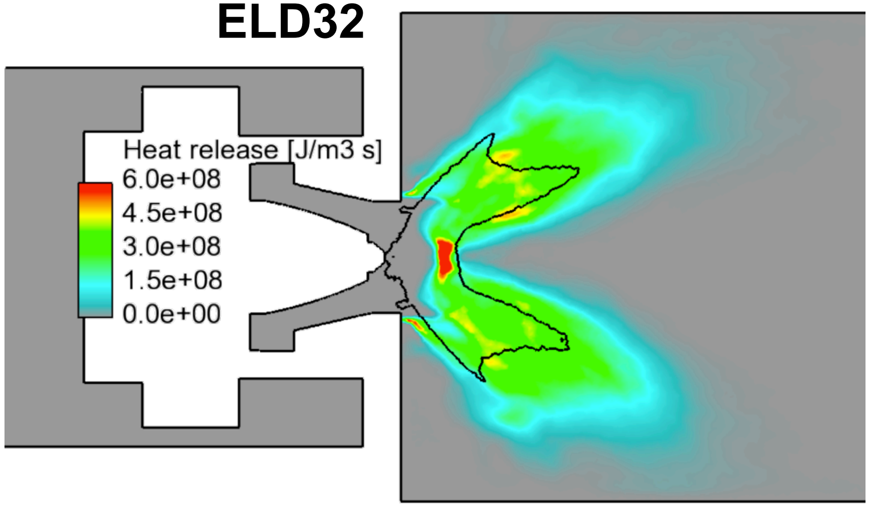
ELD10



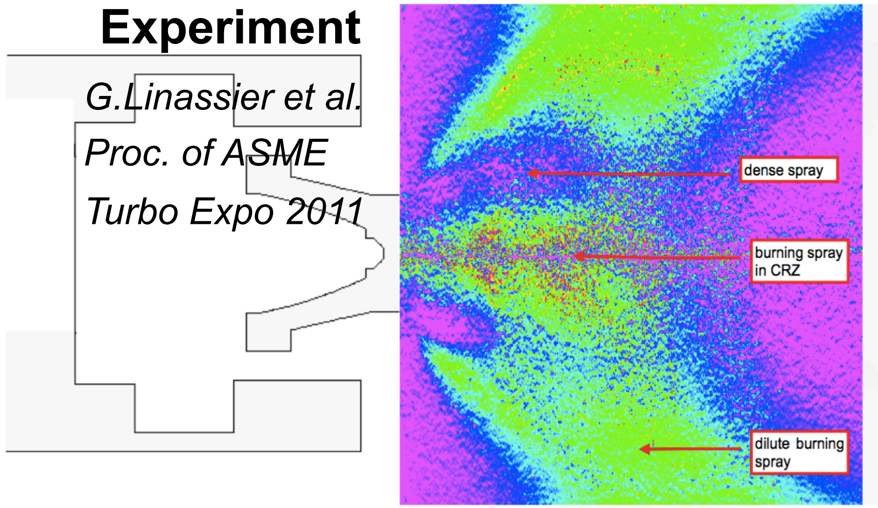
ELRR



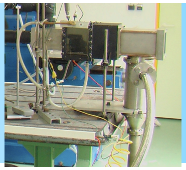
ELD32



Experiment



Mean Heat release field in the median cut plane with isoline of liquid volume fraction ($\alpha_l = 10^{-5}$)



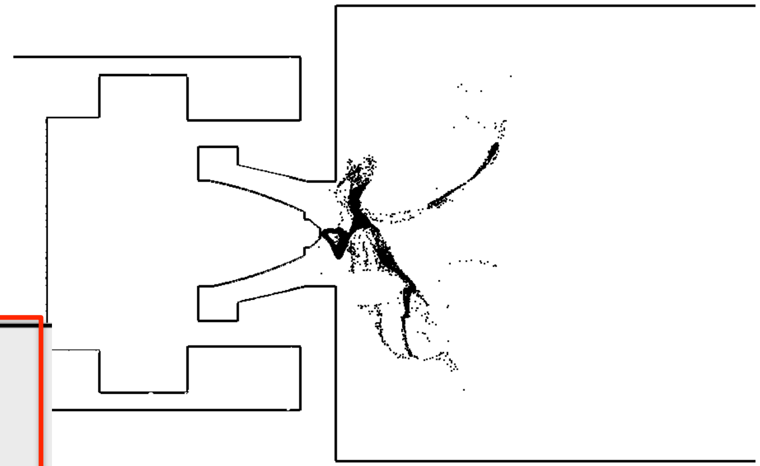
Application to MERCATO

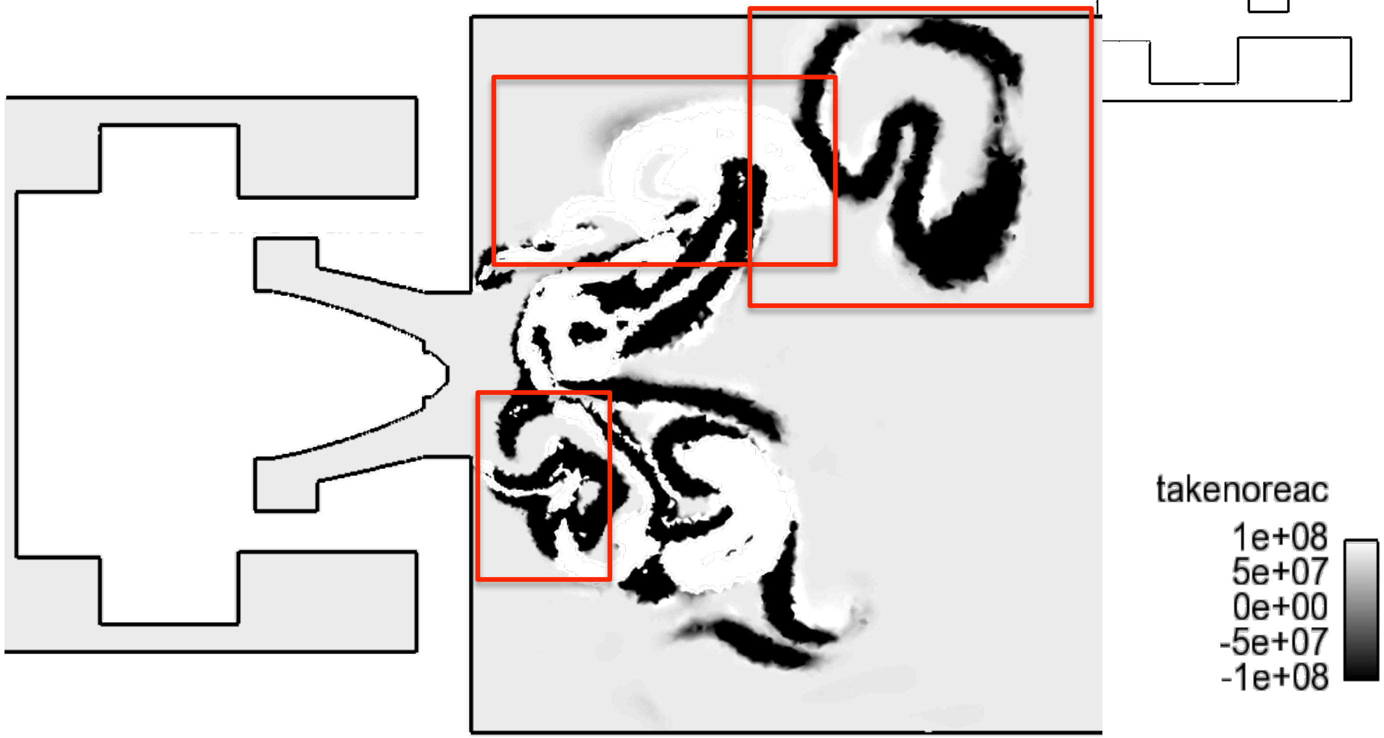
$$Takeno = \nabla Y_F . \nabla Y_O * \left| H_R \right|$$

White Takeno = premixed

Black Takeno = diffusion

drops





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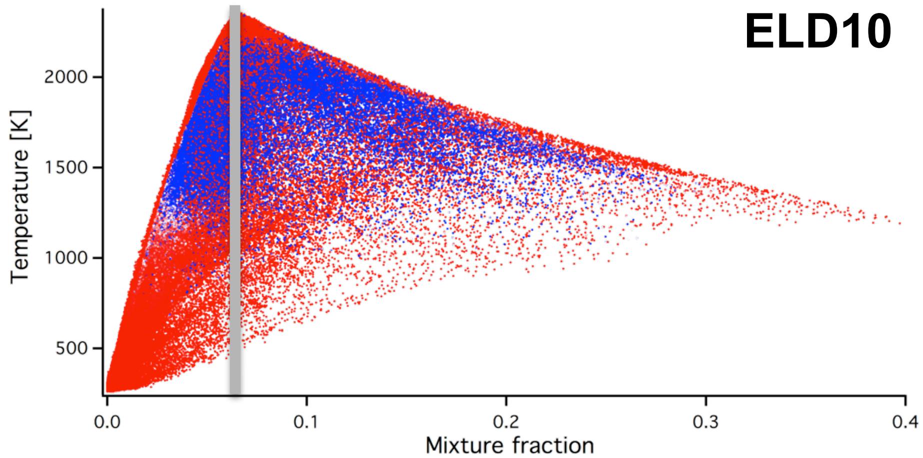
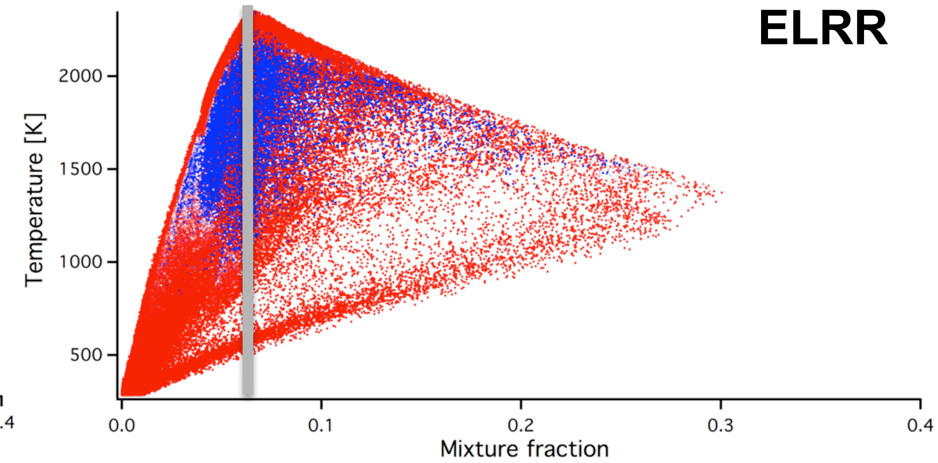
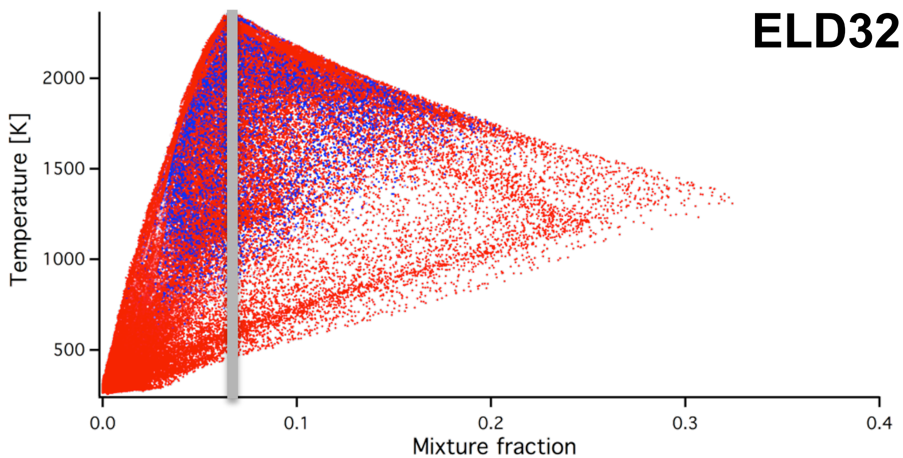






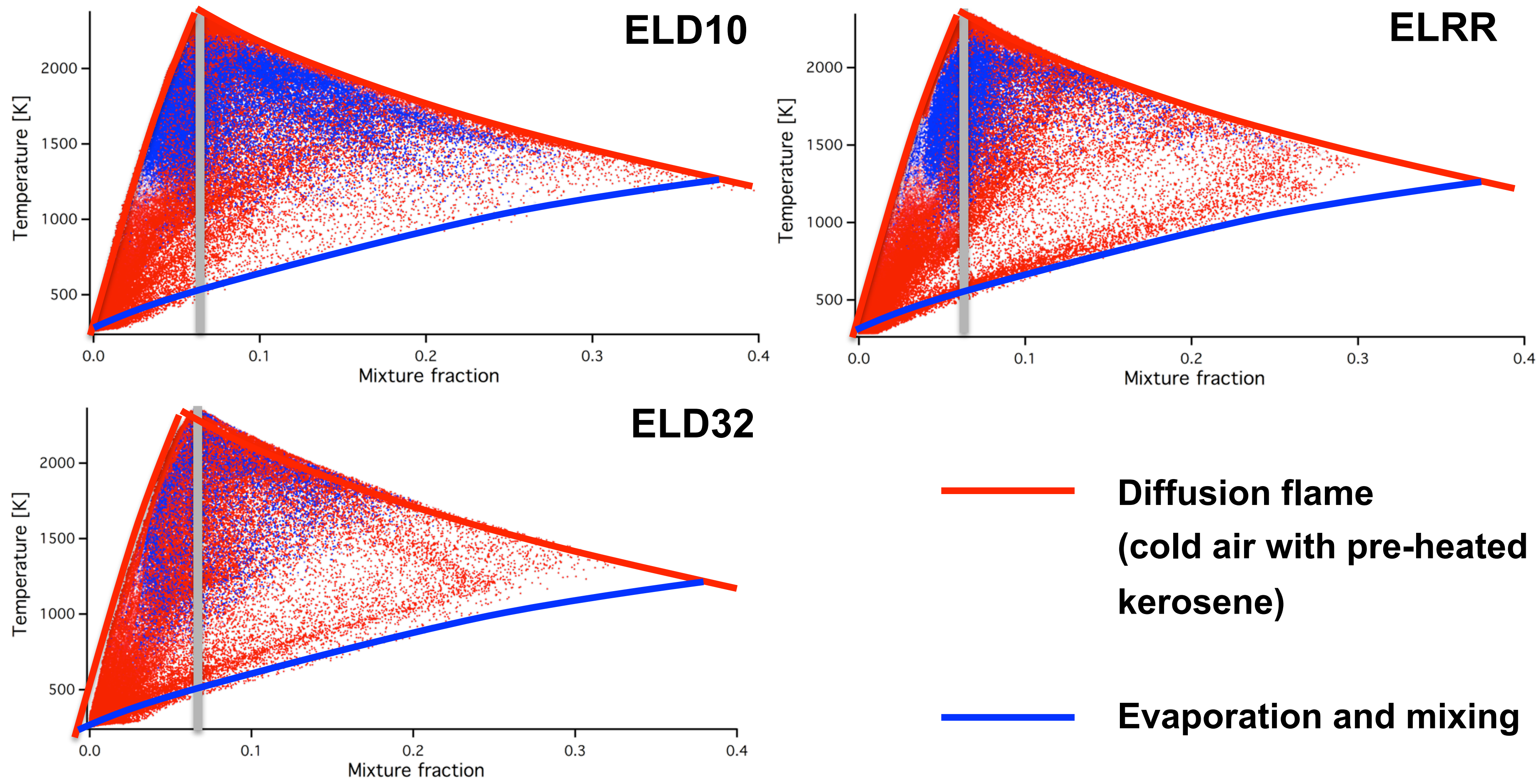
Red = diffusion

Blue = premixed

$$z = \frac{Y_C - Y_C^O}{Y_C^F - Y_C^O}$$

Scatterplots of temperature versus mixture fraction colored by Takeno index (grey line = stoechiometric mixture fraction z_{st} = 0.0625)

Application to MERCATO



Scatterplots of temperature versus mixture fraction colored by Takeno index
(grey line = stoechiometric mixture fraction z_{st} = 0.0625)

CONCLUSIONS

- **LES of two-phase reacting flows in complex geometries** are now possible with **good accuracy and prediction quality**

- Liquid fuel generates **complex flame structures**

- **Polydispersion** has a strong impact on cold spray dispersion but does not modify significantly the flame shape and structure.

  Using D32 in a monodisperse reacting spray gives good result

- **Numerous issues** are still open:
  - Simulation of atomisation
  - Liquid phase introduces new flame structures which require new combustion models:
    - Non adiabatic
    - Variable equivalence ratios through the flame
    - New combustion regimes (isolated droplets)
    - Complex chemistry
- Spray flame **measurements** are helpful

QUESTIONS