Flow characteristics and turbulence analysis of a large-scale pressure-atomized spray

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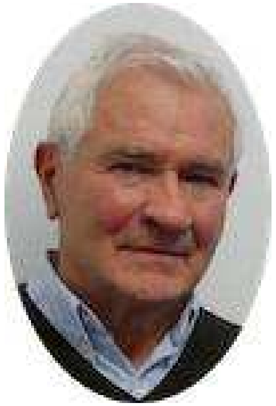


EJH2016 : Emil Hopfinger Colloquium 2016
11–13 May 2016, Grenoble, France

- ✓ Introduction
- ✓ Experimental details
- ✓ Results (with comparison with modeling data)
- ✓ Conclusion - perspectives

- Stevenin, C, Vallet, A, Tomas, S, Amielh, M, Anselmet, F, Eulerian atomization modeling of a pressure-atomized spray for sprinkler irrigation
Intern. J. Heat Fluid Flow, Vol. 57, pp. 142-149 (2016)
- Stevenin, C, Tomas, S, Vallet, A, Amielh, M, Anselmet, F, Flow characteristics of a large-size pressure-atomized spray using DTV
Intern. J. Multiphase Flow, Vol. 84, pp. 264–278 (2016)

Introduction

Sprinkler irrigation :

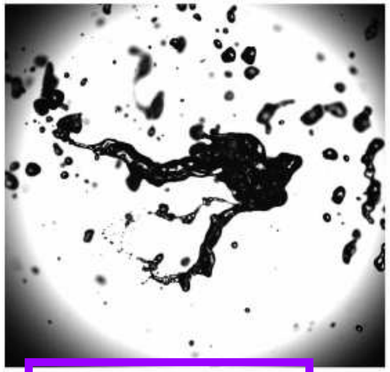
high range
non-spherical droplets
poly-dispersed droplets

How can we control the water distribution (droplet velocity and size)

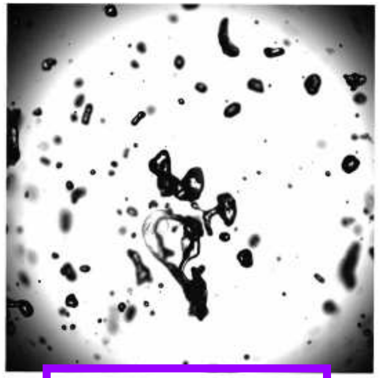
high Reynolds and Weber flow
interaction with the atmosphere
pollutant dispersion (waste water reuse)

$x/d_{nozzle} \in [0; 12]$

$x/d_{nozzle} \in [64; 76]$



$x/d_{nozzle} \in [451; 463]$



$x/d_{nozzle} \in [886; 898]$

Jets involved in sprinkler irrigation are very different from usual sprays :

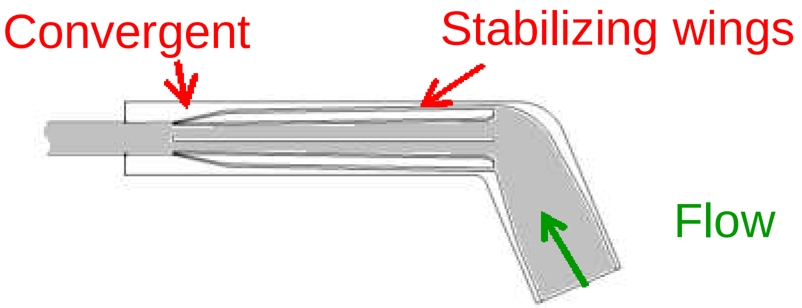
- atomization is wished to be as gradual as possible
- these jets have a very long core of liquid (more than 210 nozzle diameters)
- the flow is composed of three-dimensional liquid fragments
- large variety of scales are present
  (ratio of the large turbulent scales over the smallest liquid length is about 10^3)
- droplets are poly-dispersed and also strongly non-spherical

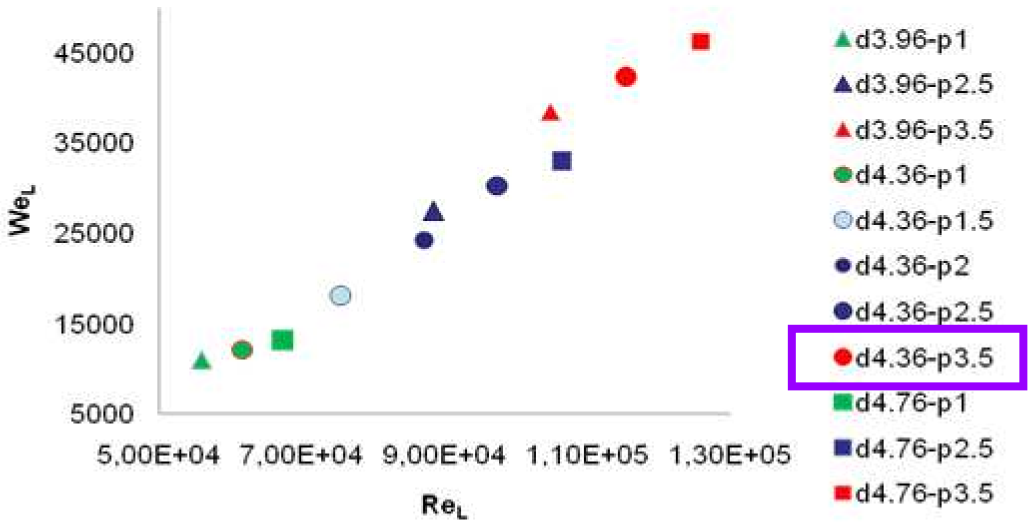
⇨ **characterize these (two-phase) flows**

⇨ **develop/validate numerical models to improve irrigation efficiency**

Experimental details

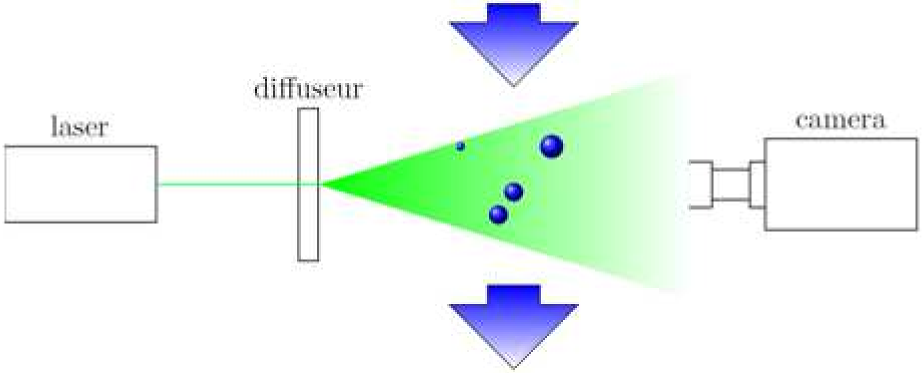
Fluid	water
Diameter of the nozzle	3,96; 4,36 et 4,76mm
Mean velocity at nozzle outlet	14 - 26 m/s
ρ_L/ρ_G	830
Reynolds number at the nozzle ($Re_L = \rho_L u0d/\mu L$)	56.000 - 158.000
Weber number at the nozzle ($WeL = \rho_L u_0^2 d/\sigma$)	11.000 - 73.000
Ohnesorge number at the nozzle	0,0017 - 0,0019



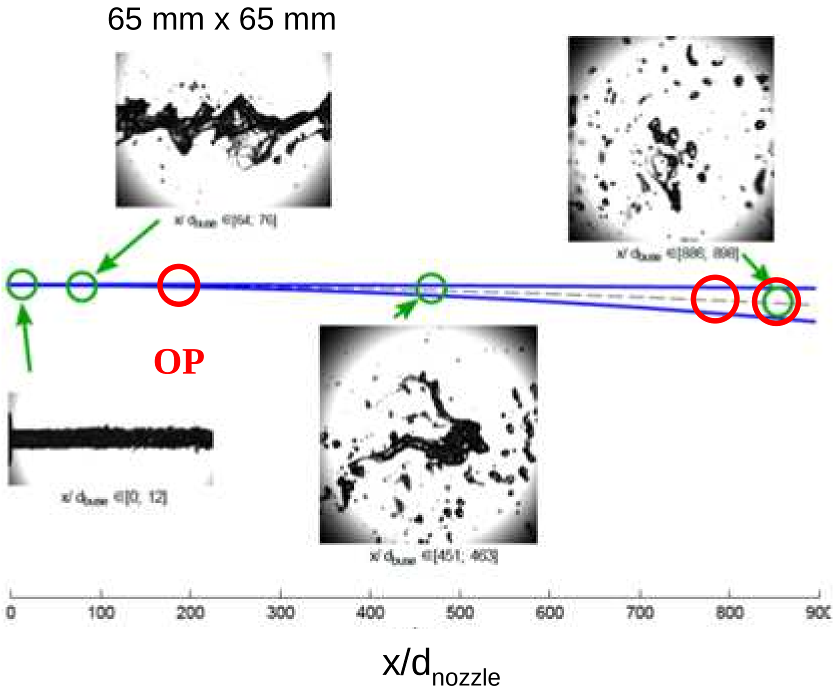


RB46 Rainbird©

The shadowgraphy experiments



Droplet Tracking Velocimetry (DTV)
(schematic view : jet is actually horizontal)



From liquid core to dispersed phase

- ✓ Dantec Dynamics:
  - Laser: Litron Nd :YAG 135 mJ
  - Camera: Hisense 4M 12-bit 2048x2048 pix
  - Lens: 105mm F2.8 DG macro lens (Sigma)
- ✓ Resolution: 30 pixels/mm
- ✓ Time between pulses : 30 µs (flash 4ns)
- ✓ 500 images

\+ Optical-fiber probe (**OP**, A2 Photonic Sensors)
at x/d_{nozzle} =[200; 780; 890]

\+ Laser Doppler Anemometry (2D LDA, Dantec Dynamics)
with an Argon ion 514.5 nm laser (4W Spectra Physics)
for $0 < x/d_{nozzle} < 900$ (*in progress*)

Specific calibration to estimate depth of field

PIV camera

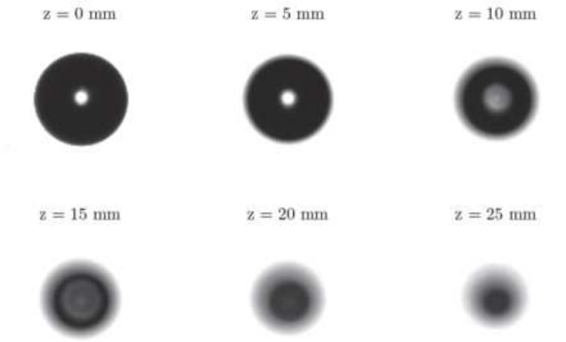
Vertical translation
(mm displacement)

Glass sphere put on
a glass slide

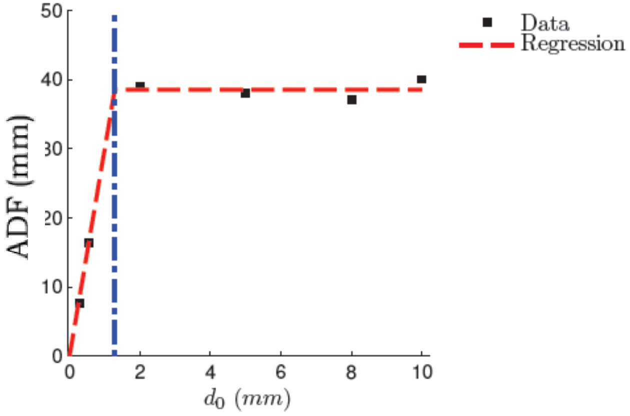
Diameters:
[0.3;0.5;2;5;8;10] mm
Displacement range:
[-60;60] mm
Step : 1mm

Light diffuser

Dantec Dynamics



Glass sphere (d=2mm) at several distances from focal plane



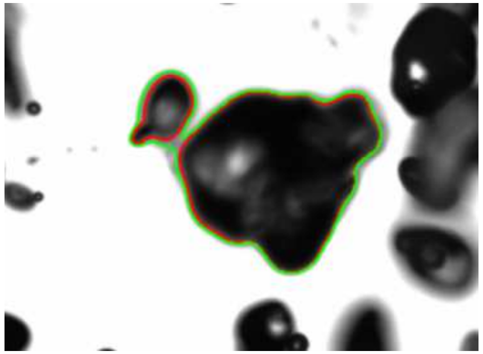
Apparent Depth of Field as a function of the diameters of the glass beads
(the smallest objects, d<1.2 mm, are not well detected)

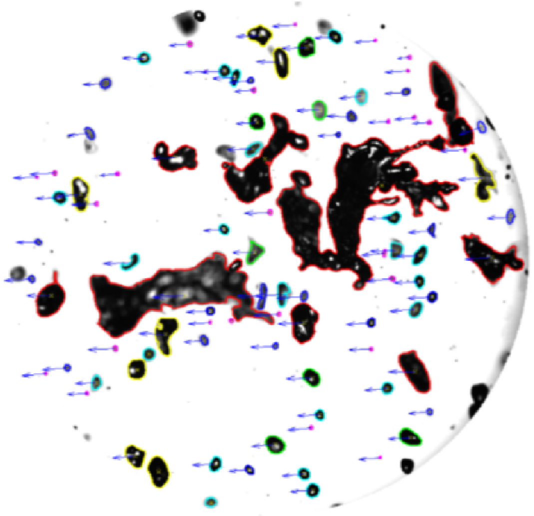
New contour detection

From contour detection for droplet tracking to meet the need of simultaneous treatment for droplet sizes and velocities

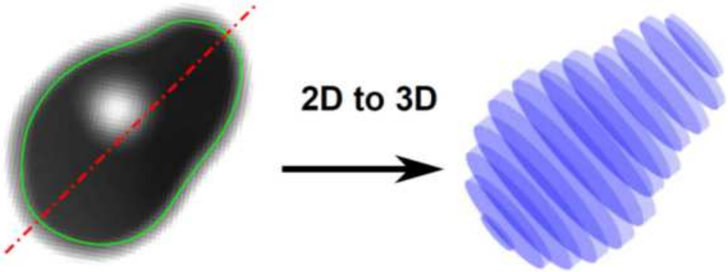
→ Histograms and PDFs → Turbulence statistics

Detect objects : wavelet transform + grey level gradients (Yon, 2003)
Separate overlapping droplets (Beucher and Lantuejoul, 1979)





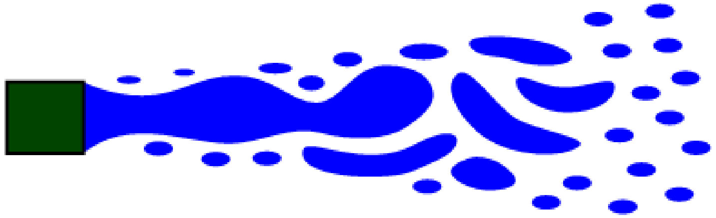
Estimate diameters for non-spherical objects (Daves et al., 1998):
(i) barycenter, (ii) principal inertia axis, (iii) surface and perimeter 2D, (iv) surface and volume (3D)



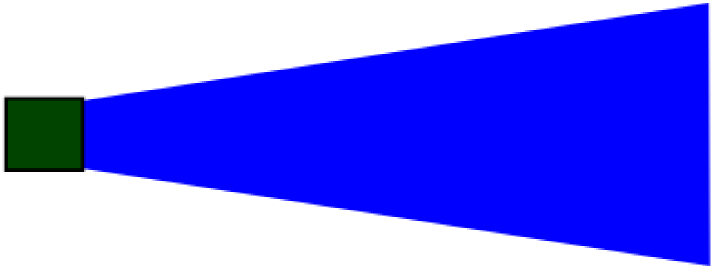
Correct droplet populations as a function of their depth of field measurement (Stevenin, 2012)

A few words about the modeling approach (k/ε or RSM)

Real multi-phase fluid



Mixture Pseudo-fluid



$$\bar{\rho} = \overline{Y}\rho_l + \left(1 - \overline{Y}\right)\rho_g \qquad \overline{Y} = \frac{\bar{\rho}\widetilde{Y}}{\rho_l}$$

where ρ_l and ρ_g are respectively the liquid and gas density.

$\widetilde{\mathrm{Y}}$ is the liquid (mean) mass fraction
$\overline{\mathrm{Y}}$ is the liquid (mean) volume fraction

Momentum:

$$\frac{\partial \bar{\rho}\widetilde{u}_i}{\partial t} + \frac{\partial \bar{\rho}\widetilde{u}_i\widetilde{u}_j}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \widetilde{\tau_{ij}}}{\partial x_j} \boxed{- \frac{\partial \bar{\rho}\widetilde{u_i'' u_j''}}{\partial x_j}}$$

Mass Conservation:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho}\widetilde{u}_i}{\partial x_i} = 0$$

Mass Fraction Transport:

$$\frac{\partial \bar{\rho}\widetilde{Y}}{\partial t} + \frac{\partial \bar{\rho}\widetilde{u}_i\widetilde{Y}}{\partial x_i} = \boxed{- \frac{\partial \bar{\rho}\widetilde{u_i'' Y''}}{\partial x_i}}$$

Specific Interface Surface:

$$\boxed{\frac{\partial \bar{\Sigma}}{\partial t} + \frac{\partial \widetilde{u}_i\bar{\Sigma}}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\frac{\nu_t}{\sigma_{\Sigma}}\frac{\partial \bar{\Sigma}}{\partial x_i}\right) = (A+a)\,\bar{\Sigma} - V_a\bar{\Sigma}^2}$$

The modeled equations for this pseudo-fluid were implemented into a customized *OpenFOAM* transient solver.

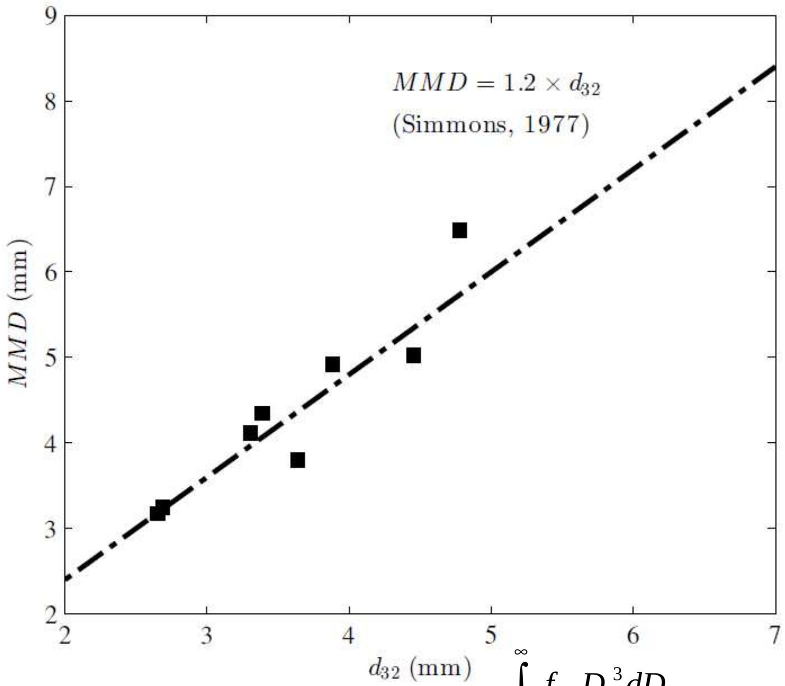
Current development includes a basic variable density *k-ε* turbulence model and the liquid/air interface transport.

The main challenge is to expand and explore other turbulence models while keeping convergence in a reasonable computational time.

From $\overline{\Sigma}$ we infer the Sauter mean diameter d_{32}: $d_{32} = \dfrac{6\,\overline{\rho}\,\widetilde{Y}}{\rho_l\,\overline{\Sigma}}$

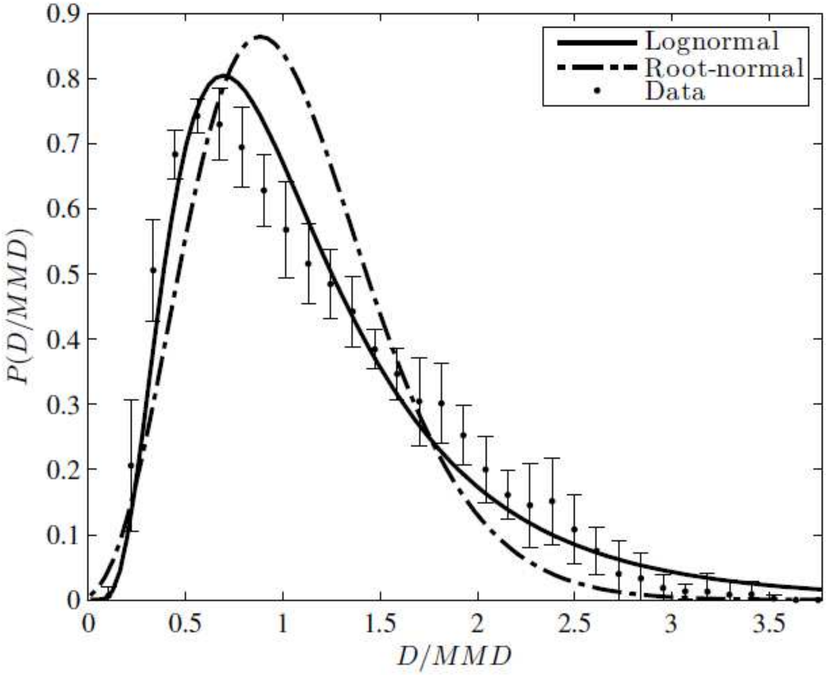
Experimental results

Droplet size distribution



$$d_{32} = \frac{\int_0^\infty f_N D^3 dD}{\int_0^\infty f_N D^2 dD}$$

Median Mass Diameter/d_{32} = 1.2
idem diesel sprays

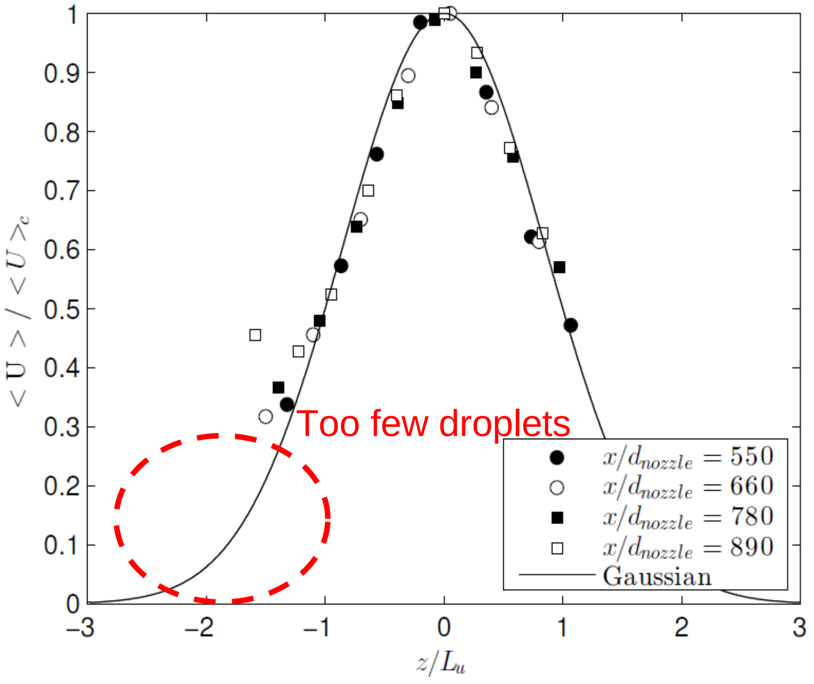


Lognormal distribution :

$$P_V(D) = \frac{1}{\sqrt{2\pi}\, s_g D} \exp\left\{ - \frac{\left[\ln(D/d_{32}) - \ln(1.2)\right]^2}{2\left[2\ln(1.2)\right]^2} \right\}$$

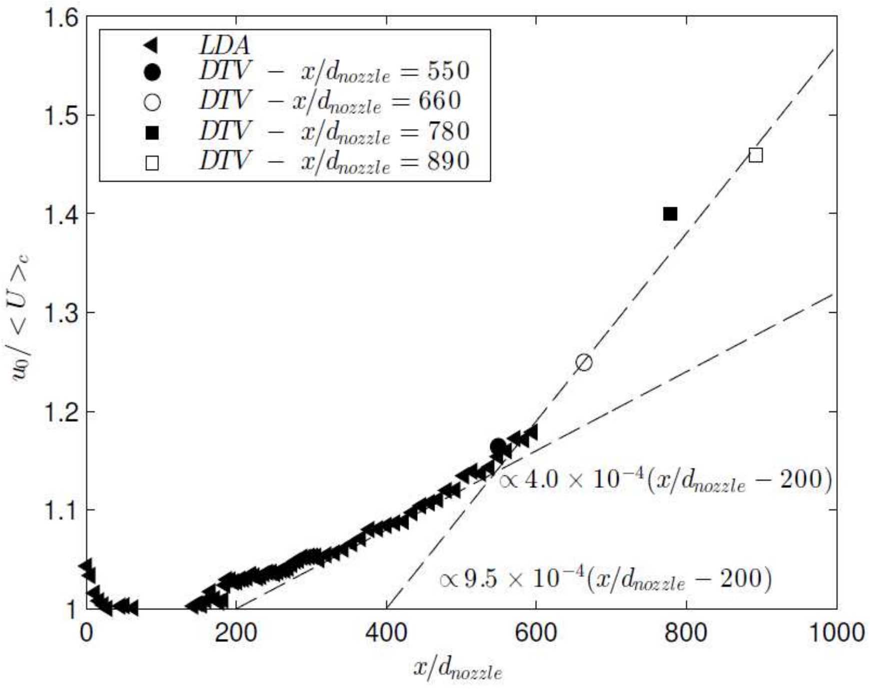
better than root-normal (Hsiang and Faeth, 1992; Sallam and Faeth, 2003).

Mean velocity



Radial profiles are symmetric

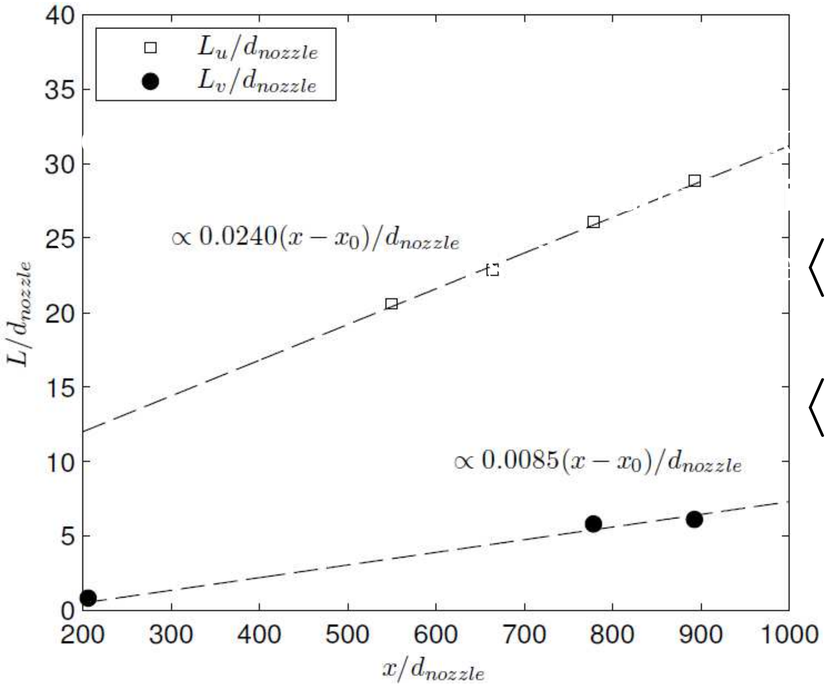
Self–similar regime obtained rapidly
(after liquid core destabilization)



concordance of LDA & DTV measurements

$0 < x/d_{nozzle} < 200$: potential core
$x/d_{nozzle} > 300$ self-similar with a decrease as x^{-1}

Mean spray dispersion



Jet half-width evolutions :

$$\langle U \rangle (z = L_u) = \frac{\langle U \rangle_c}{2}$$

$$\langle Y \rangle (z = L_y) = \frac{\langle Y \rangle_c}{2}$$

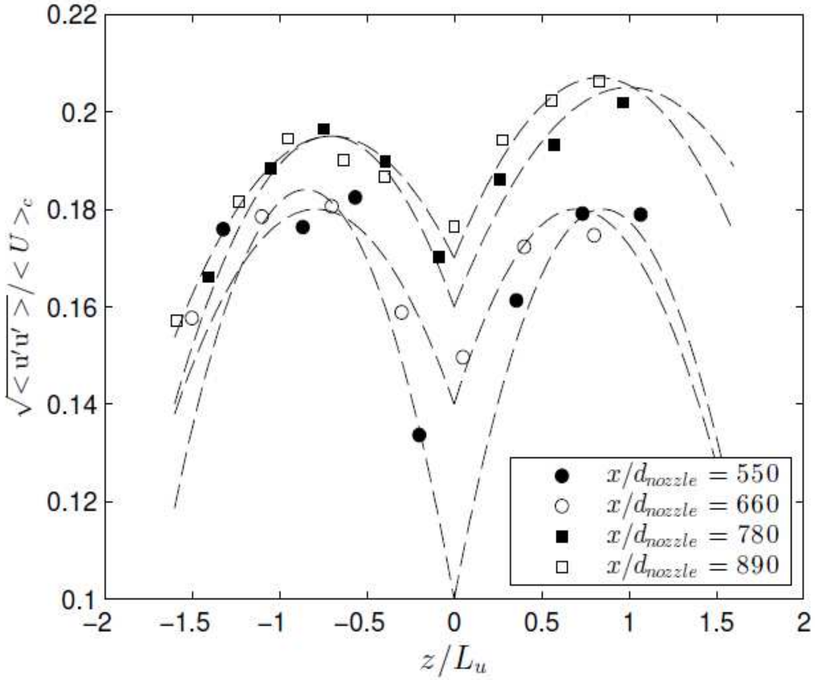
$\langle Y \rangle$: liquid volume fraction

$\langle U \rangle_c, \langle Y \rangle_c$: centerline values

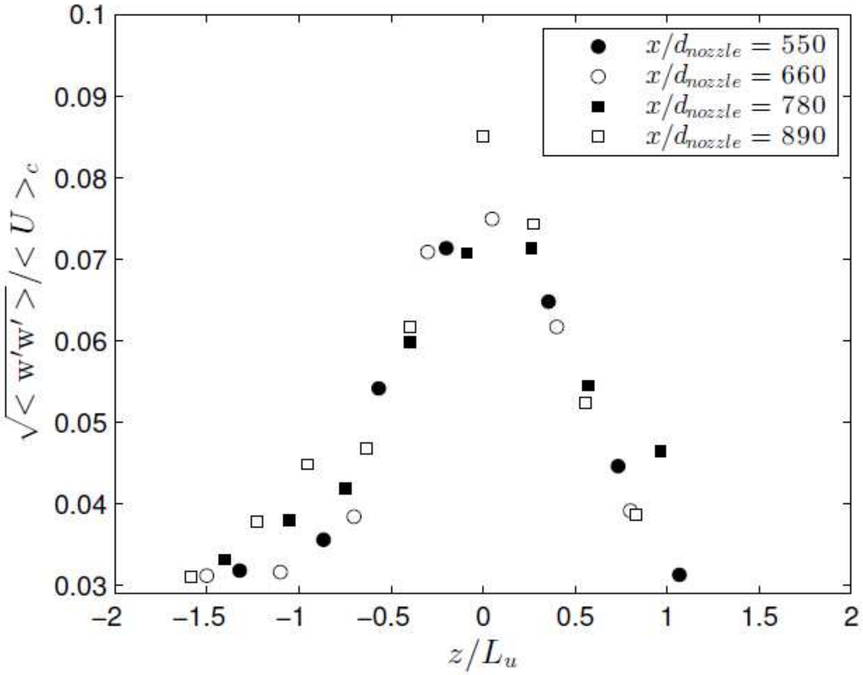
$L_i \propto S_i (x - x_0) \quad S_u = 0.024$ < classical value around 0.084 (Wygnanski and Fiedler, 1969)
but ~ diesel spray: 0.025 (Georjon, 1998) and 0.021 (Boedec, 1999)

$L_y < L_u \neq$ single phase jets (→ due to large droplets ?)

Turbulence properties : velocity variances

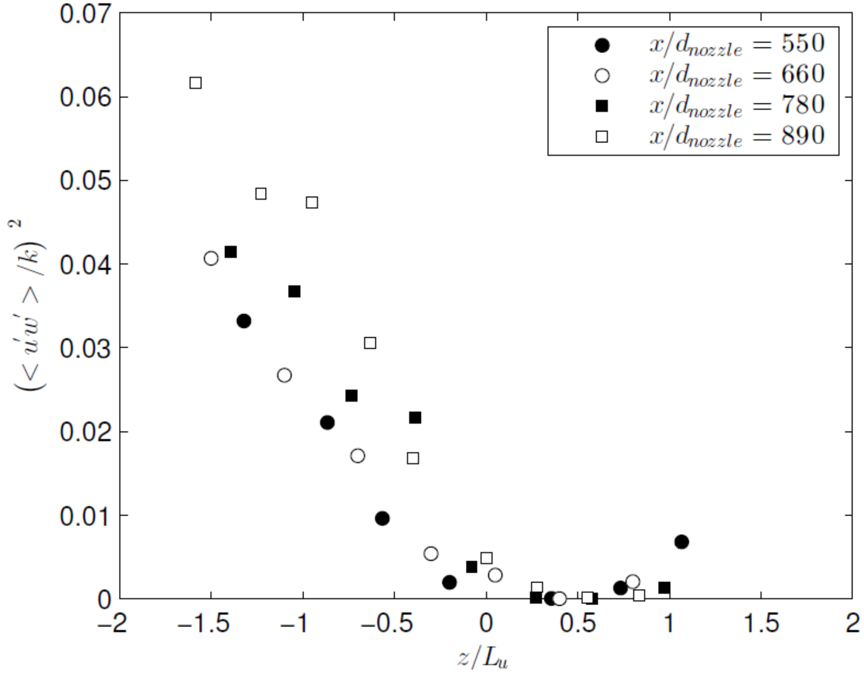


Self-similarity not yet reached
≠ single phase jets for which it is right after the potential core
<u'u'> maximal around the half-width (maximal shear)



<w'w'>/<u'u'> ~0.2 → large anisotropy
~ diesel spray (Boedec, 1999)
+ low <w'w'> values → spreading rate lower than for classical jets

Turbulence properties : Reynolds stress <u'w'> and C_μ



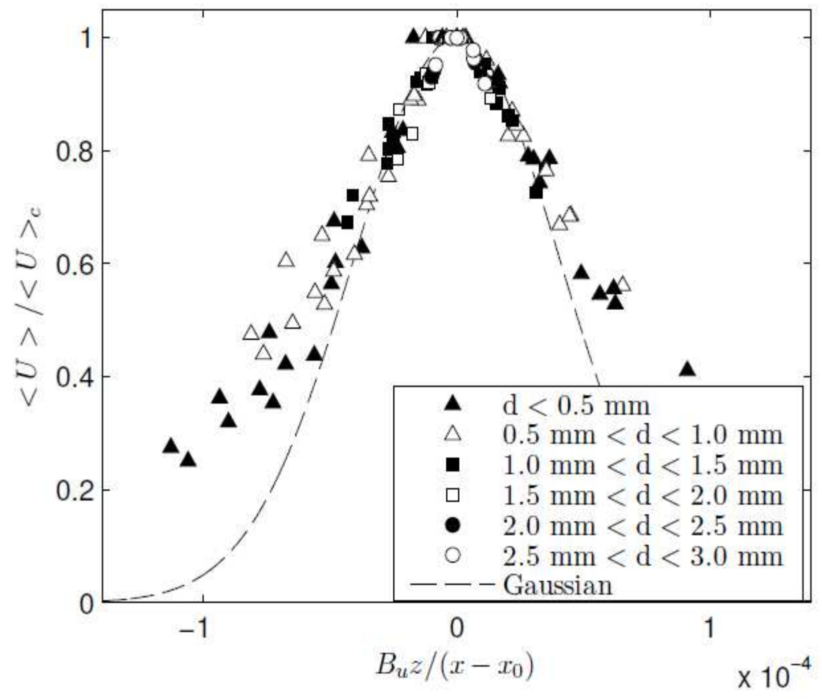
$$-<u_i'u_j'> = \nu_T\left(\frac{\partial <U_i>}{\partial x_j} + \frac{\partial <U_j>}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij}$$

$$\nu_T = C_\mu \frac{k^2}{\varepsilon}$$

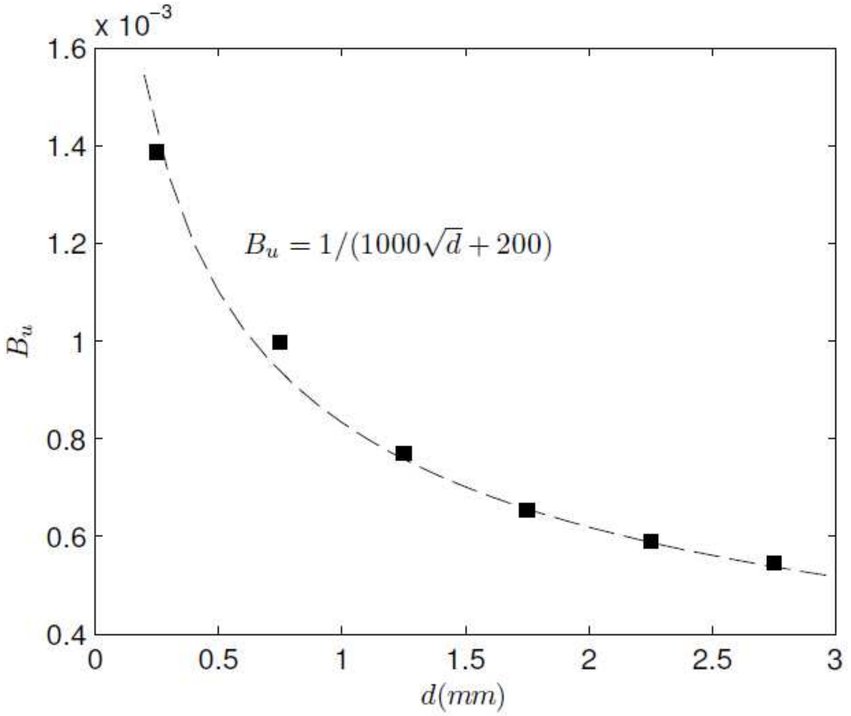
Max. around $z/L_u = -1.5$ → $C_\mu \sim 0.05$
$\neq 0.09$

But OK with single phase jets
(Rodi and Spalding, 1970; Spalding, 1983)

Mean velocities by class of diameters



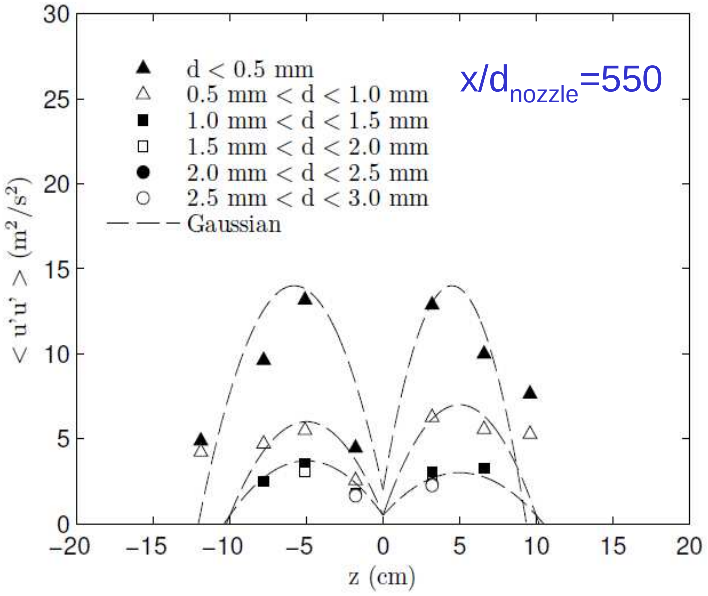
Self-similar
Centerline value decreases as $B_u x^{-1}$
B_u: coefficient introduced to take into account diameter impact on axial velocity



$B_u \sim d^{-1/2}$

$\langle U \rangle_{(d<0.5\ mm)}$ decay x2 $\langle U \rangle_{(d>2\ mm)}$

Turbulence properties : velocity variances by class of diameters



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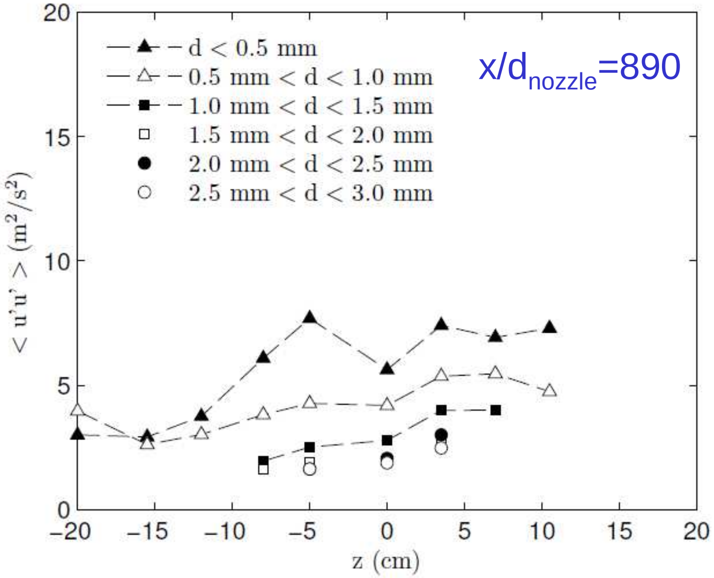
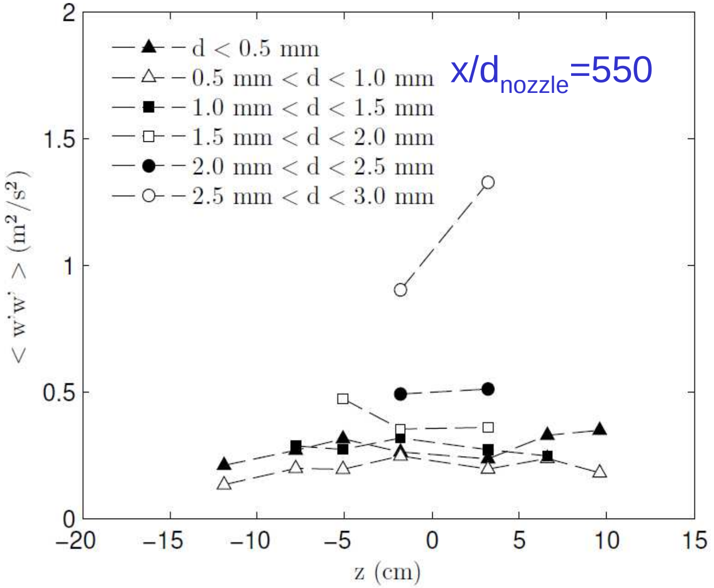
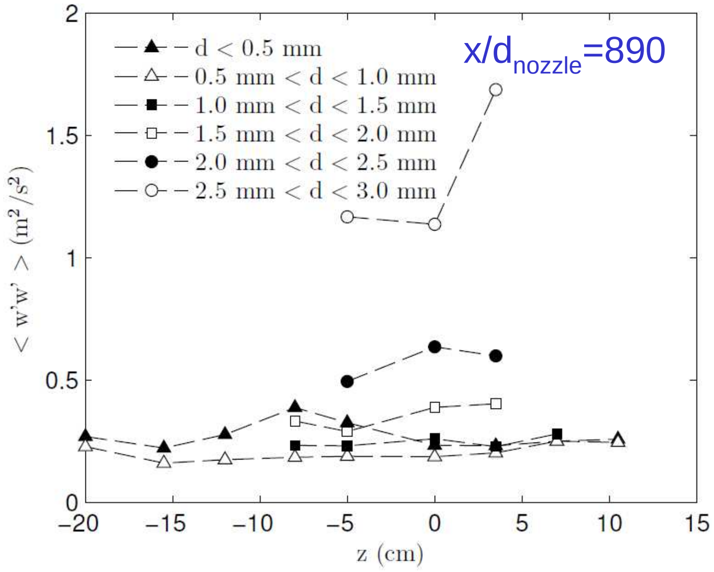
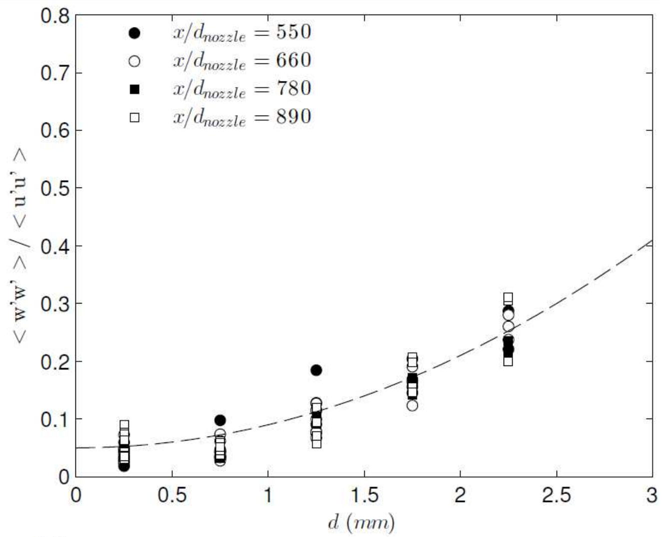




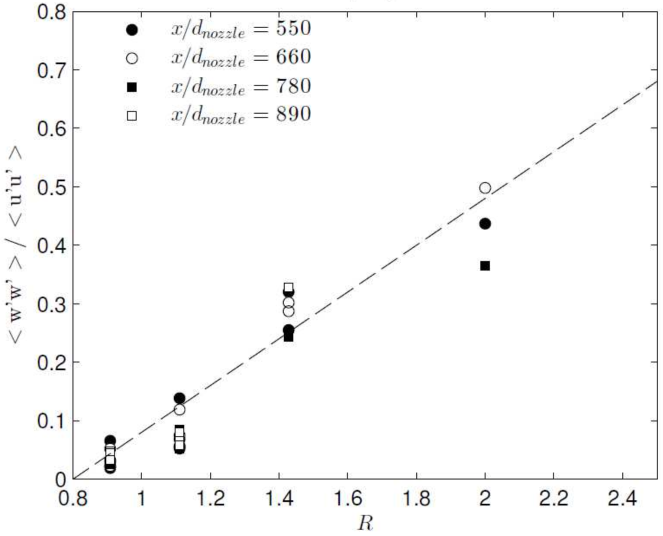
<w'w'>



Turbulence properties :
anisotropy factor vs droplet diameter and sphericity



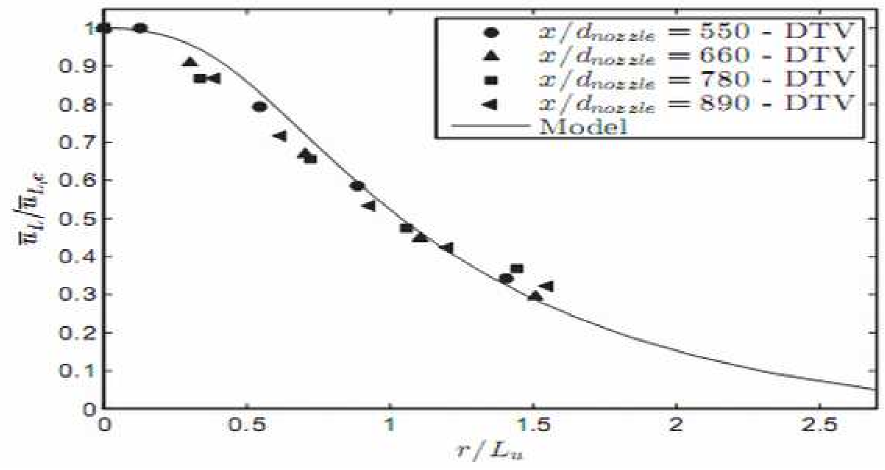
Anisotropy factor <w'w'>/<u'u'> increases with droplet size and reaches usual values around 0.5 for droplets with a diameter larger than 2mm.



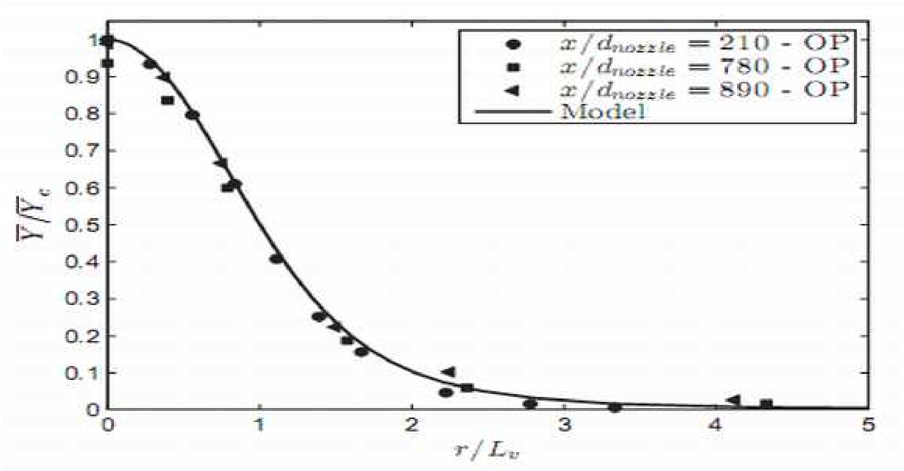
Rather similar trend for the sphericity R influence

(R=$P^2/4\pi A$ with P the droplet perimeter and A the area)

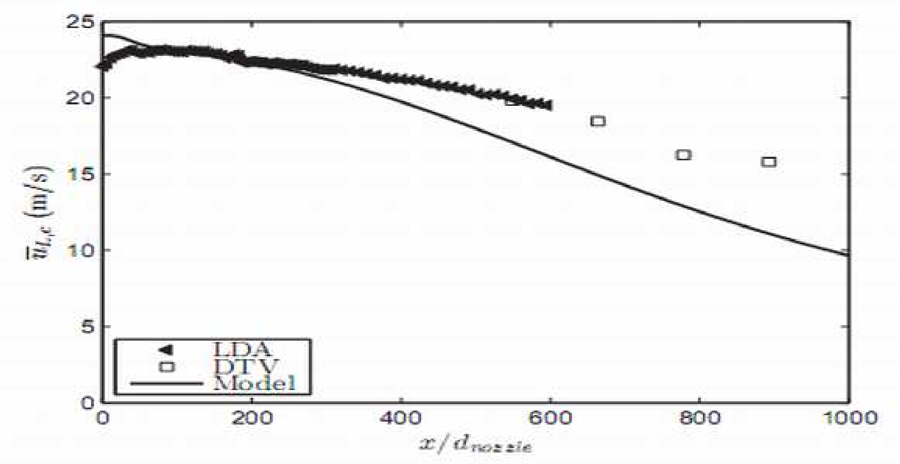
Some typical numerical results (k/ε)



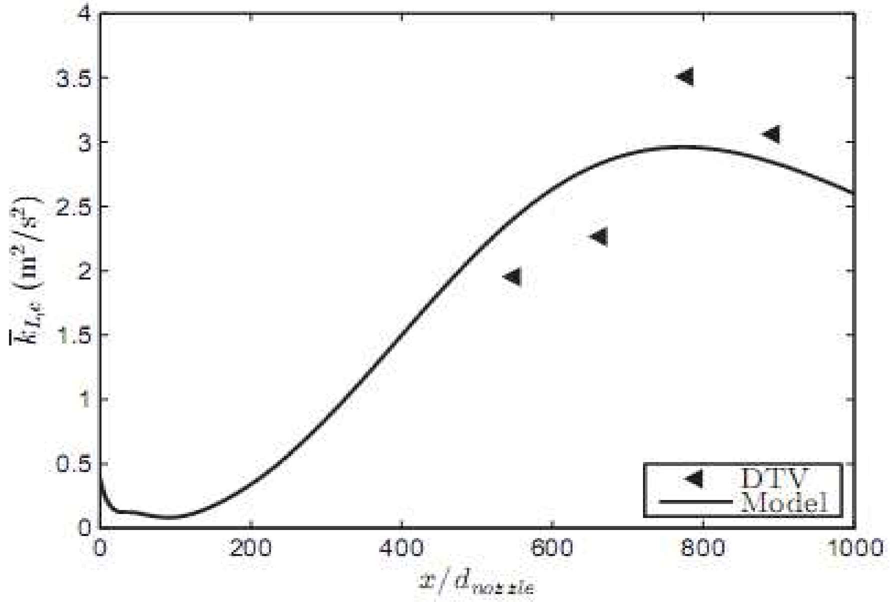
Radial evolution of the mean liquid velocity normalized by its centerline value (since $\overline{u}_{L,i} = \tilde{u}_i + \frac{\widetilde{u_i''Y''}}{\tilde{Y}}$)



Radial evolution of the mean liquid volume fraction normalized by its centerline value



Longitudinal evolution of the centerline mean liquid velocity



Longitudinal evolution of the centerline turbulent kinetic energy of the mixture (assumed equal to that of the liquid since the liquid mass fraction is larger than 0.8 for $x/d_{nozzle}<900$)

How can we improve these results with a RSM approach, and account for anisotropy effects ?

Conclusion - perspectives

- Conclusion:
  - Jet spreading rate lower than for round single phase jets
  - Droplet dynamics strongly influenced by their size
  - Considerable anisotropy
  - C_μ lower than classically observed

- Perspectives:
  - Perform refined DTV and LDV experiments to estimate air and liquid turbulence properties simultaneously
  - Characterize jet turbulence in the compact zone to analyze its impact on jet atomization and provide data for model initialization
  - Develop refined turbulence modeling (anisotropy ?)

Thank you for
your attention …