Some aspects of turbulent mixing in two phase flows

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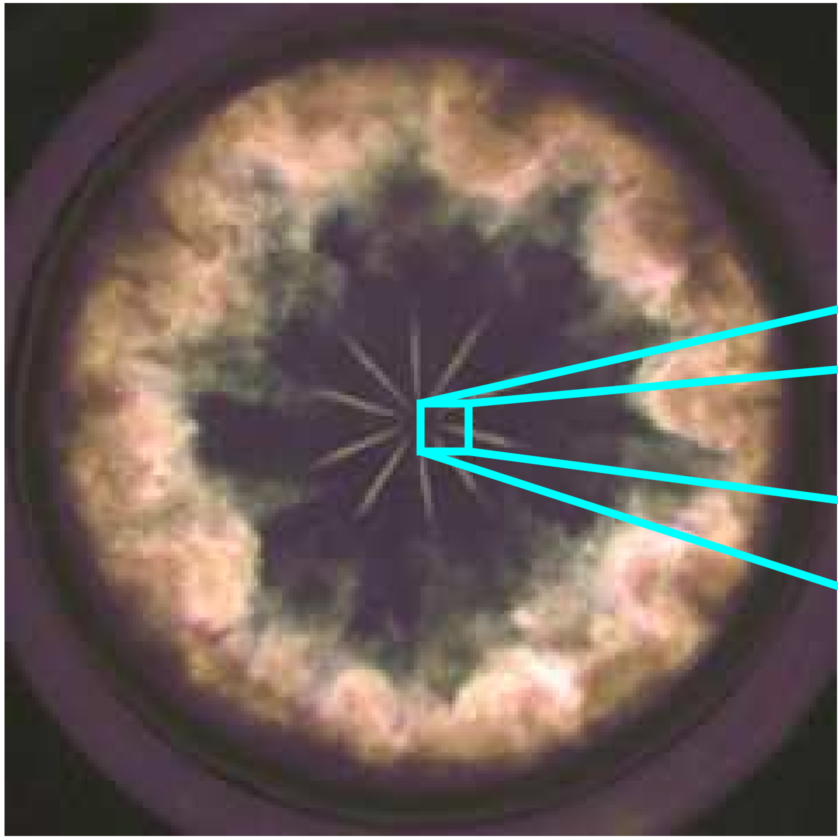
UMR 6614 CORIA
COMPLEXE DE RECHERCHE INTERPROFESSIONNEL EN AEROTHERMOCHIMIE
CNRS – UNIVERSITE et INSA de Rouen

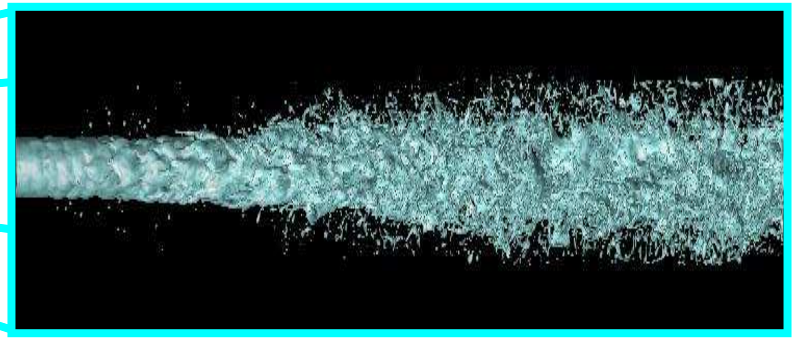
Motivations

Diesel engine → Some kind of turbulence

↓

Even at small scale





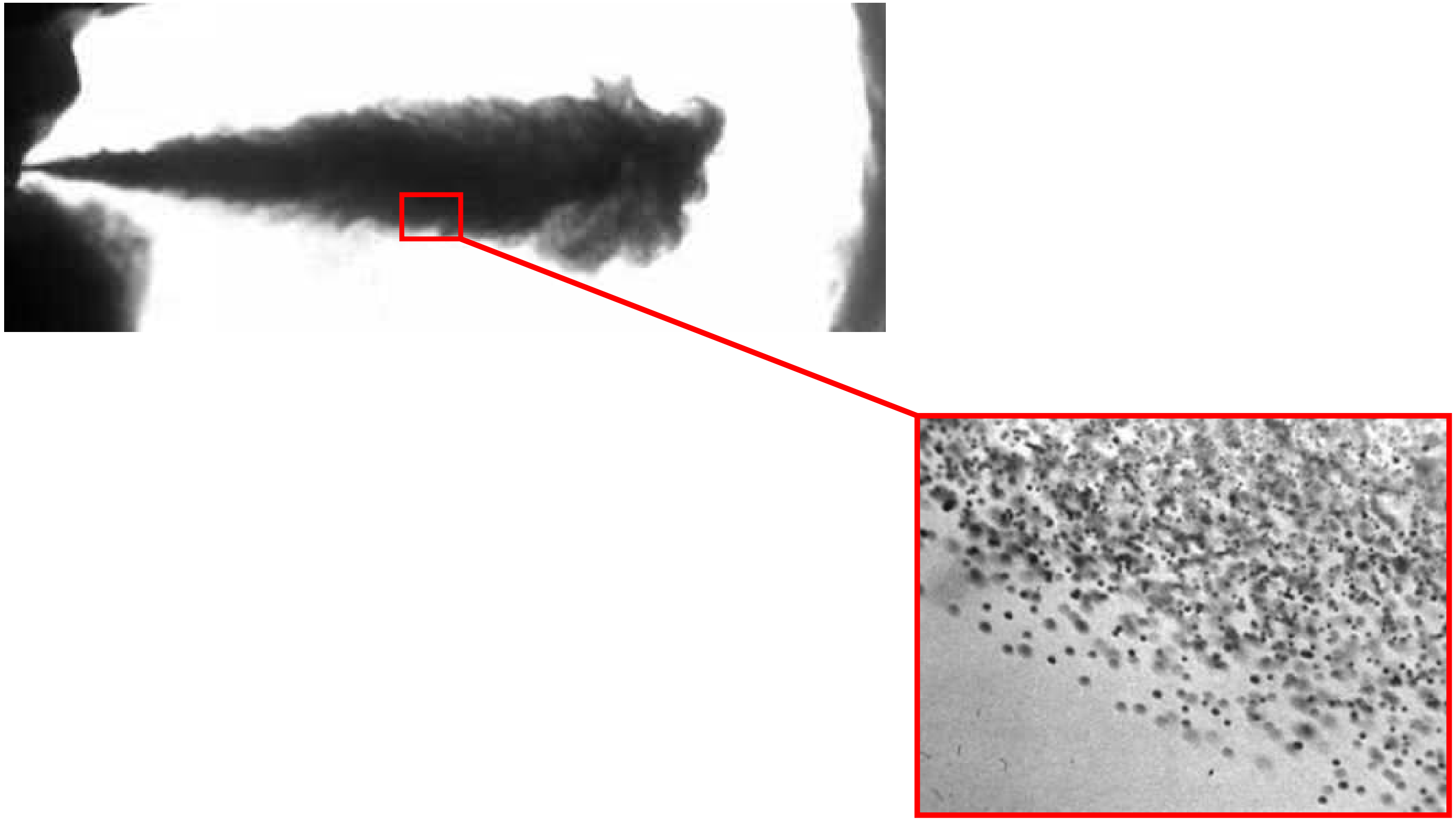
Matsui-Kosaka

→ **Key phenomena is “turbulent” mixing**

Out line

Part I : Introduction to atomization and two-phase flow modeling

Part II : Turbulence mixing approach for atomization



Part III : Turbulence, droplet, vaporization, mixing and combustion

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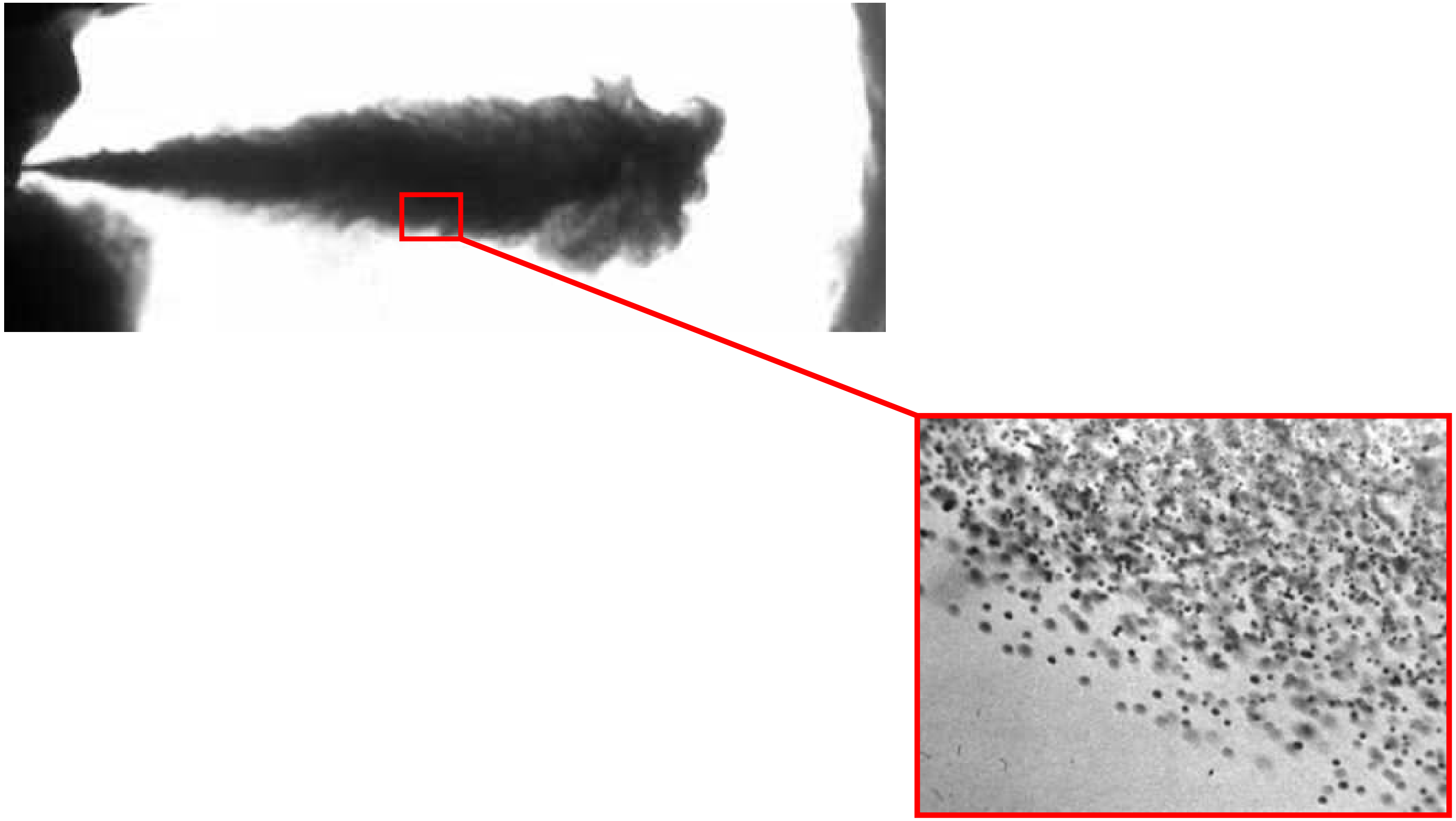
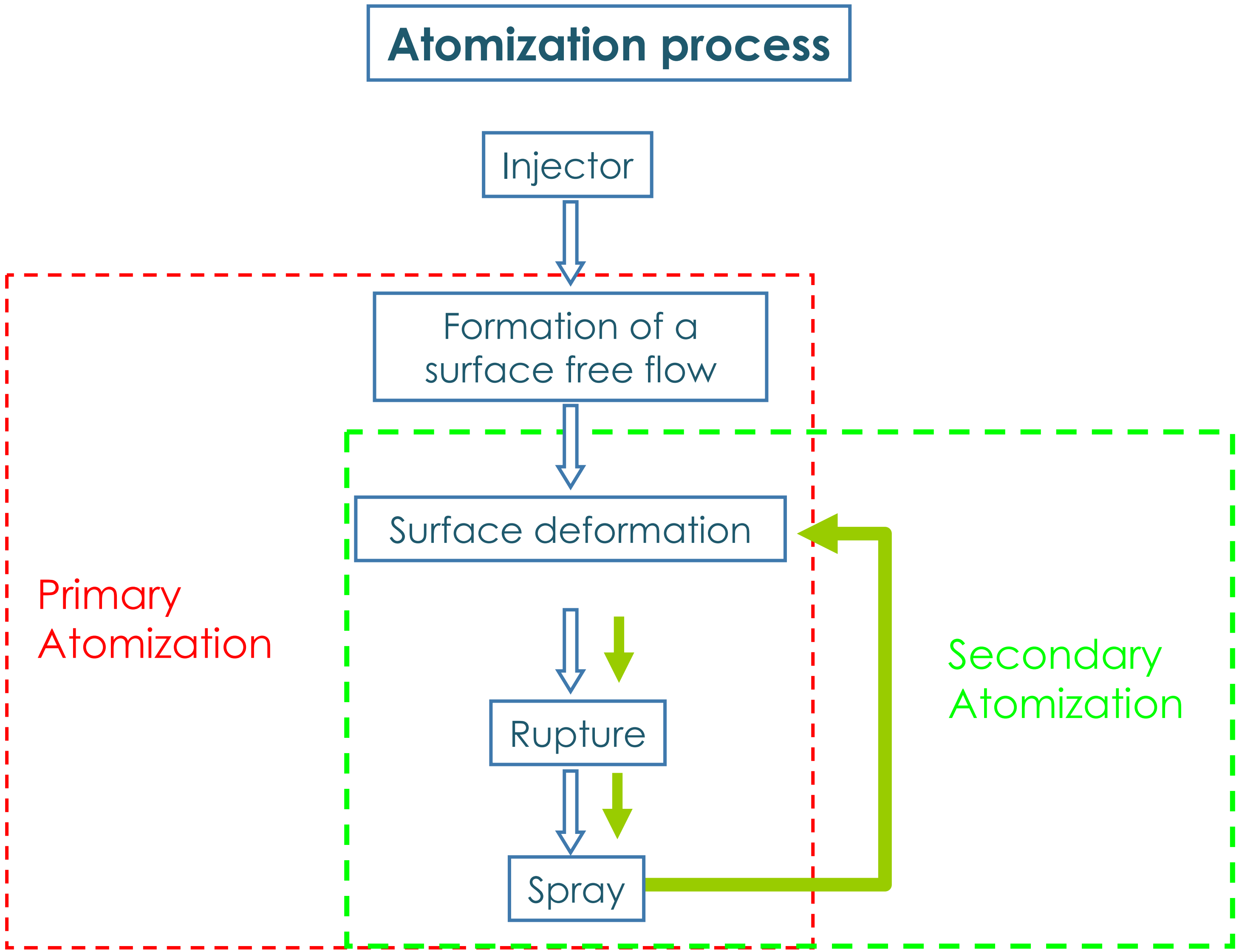


Part III : Turbulence, droplet, vaporization, mixing and combustion

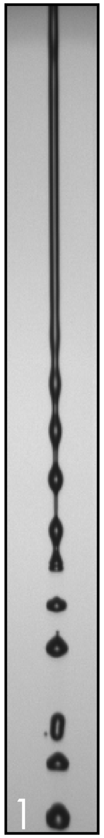
Fundamentals:

Experimental observations

Fundamental of atomization process

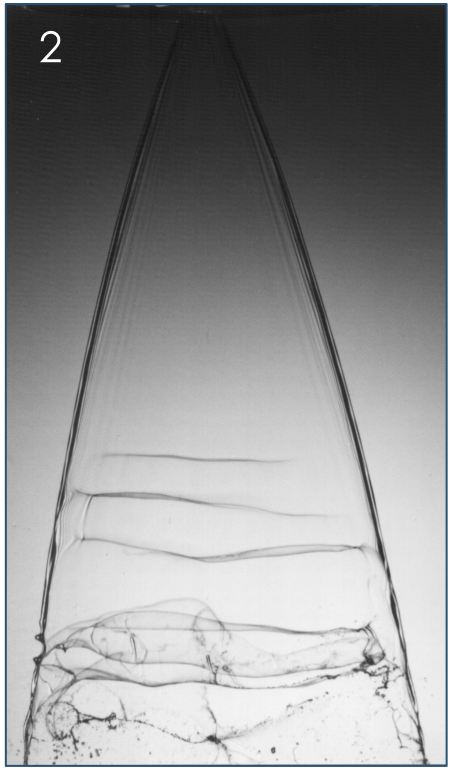


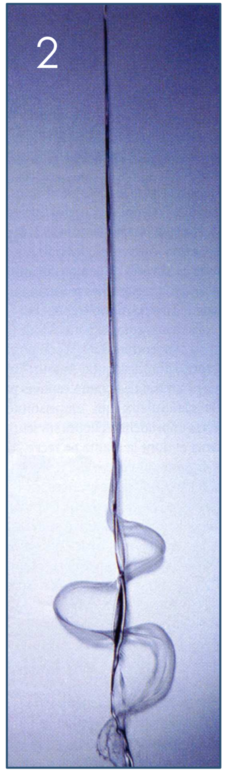
Influence of the geometry

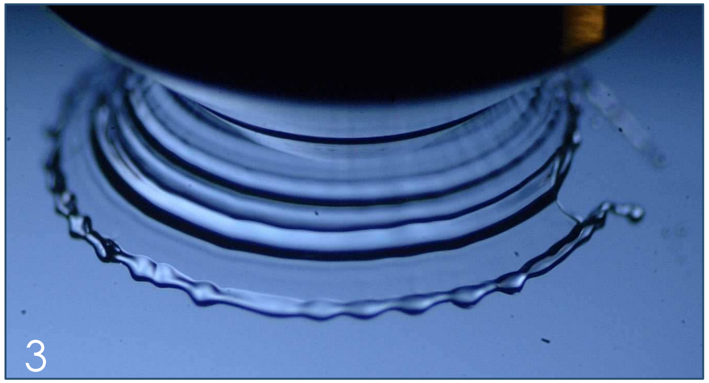


1 – Cylindrical jet : capillary instability

2 – Liquid sheet







3 – Annular sheet

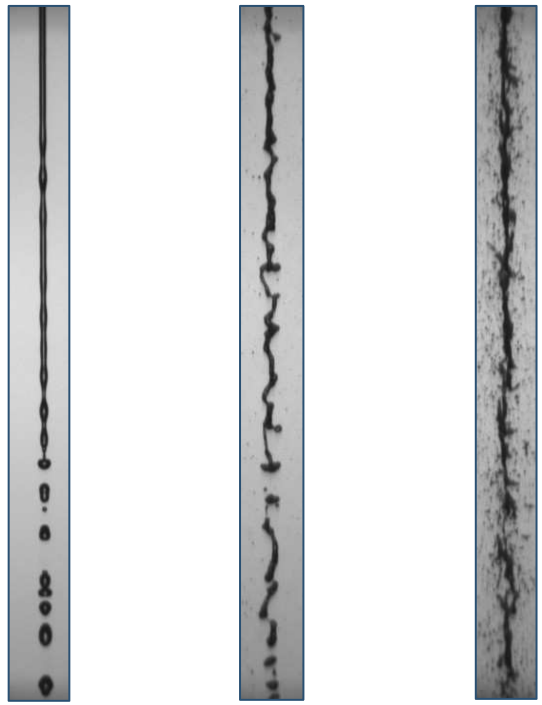
Photos CORIA

Influence of mean liquid velocity

- d = 600 µm
- Eau/air

Photos CORIA

$$Re = \frac{\rho_L U_L d}{\mu_L}$$



$$We_G = \frac{\rho_G (U_G - U_L)^2 d}{\sigma}$$

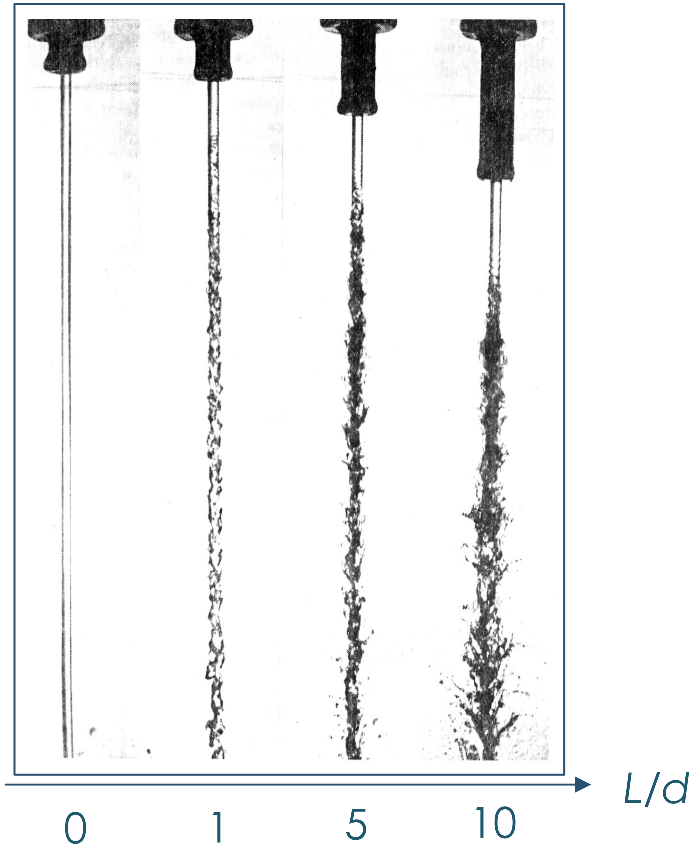
U_L	1.4 m/s	24 m/s	47 m/s
We_G	0.02	6	24

- $U_L \nearrow$ → Turbulence $\nearrow$ → Interfacial deformation → $D_G \searrow$
- $U_L \nearrow$ → $\Delta U \nearrow$ → Increase of aerodynamic forces → $D_G \searrow$

Influence of inlet velocity profile

- d = 2.54 mm
- Glycerol-eau/air
- U_L = 20 m/s
- We_G = 15

•Photos : Mc Carthy et Molloy, 1973

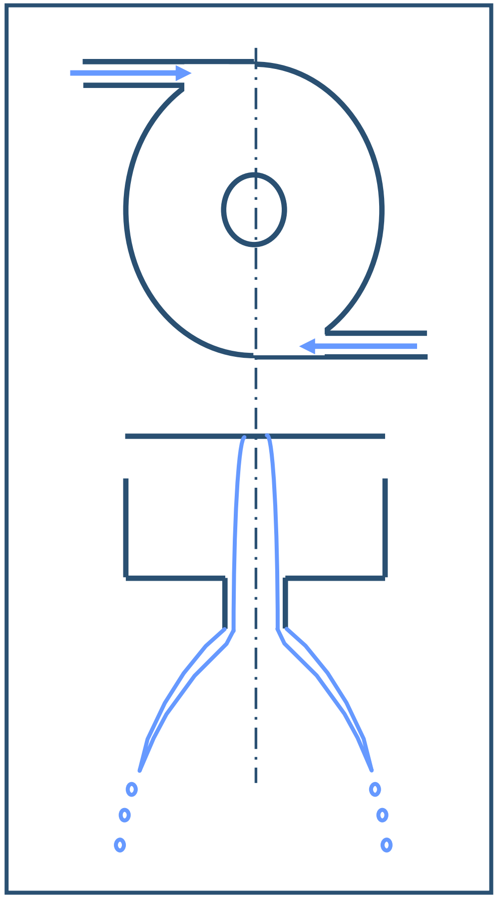


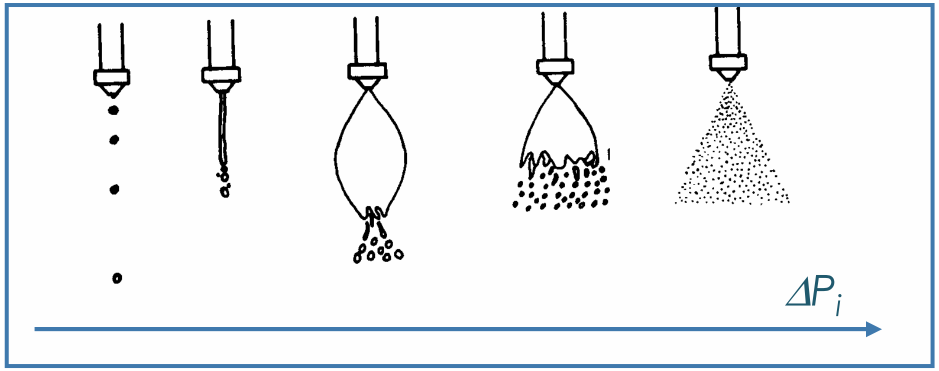
•The relaxation of the velocity profile may generate instabilities that promote the atomization process

Influence of velocity profile at the inlet

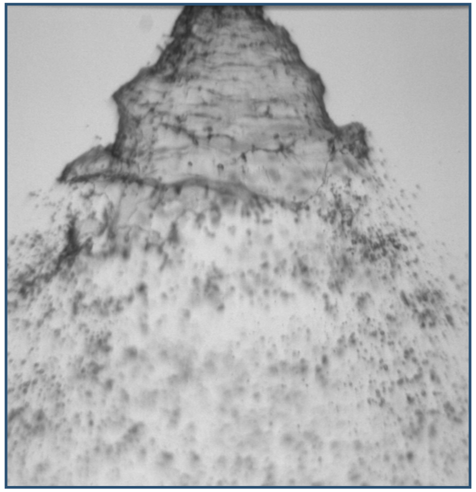
• Swirl injector

• Schematic

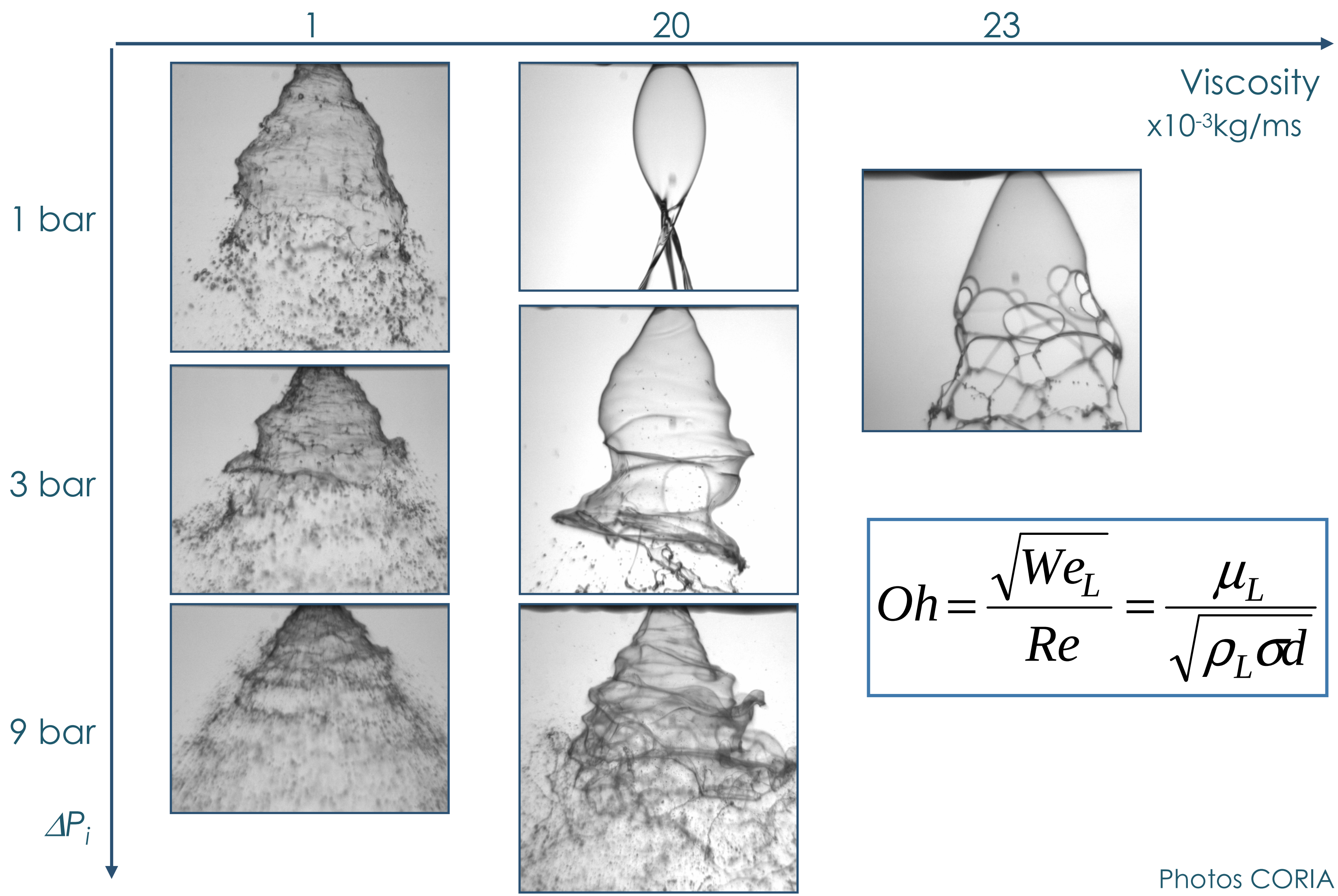




• Example



Influence liquid viscosity

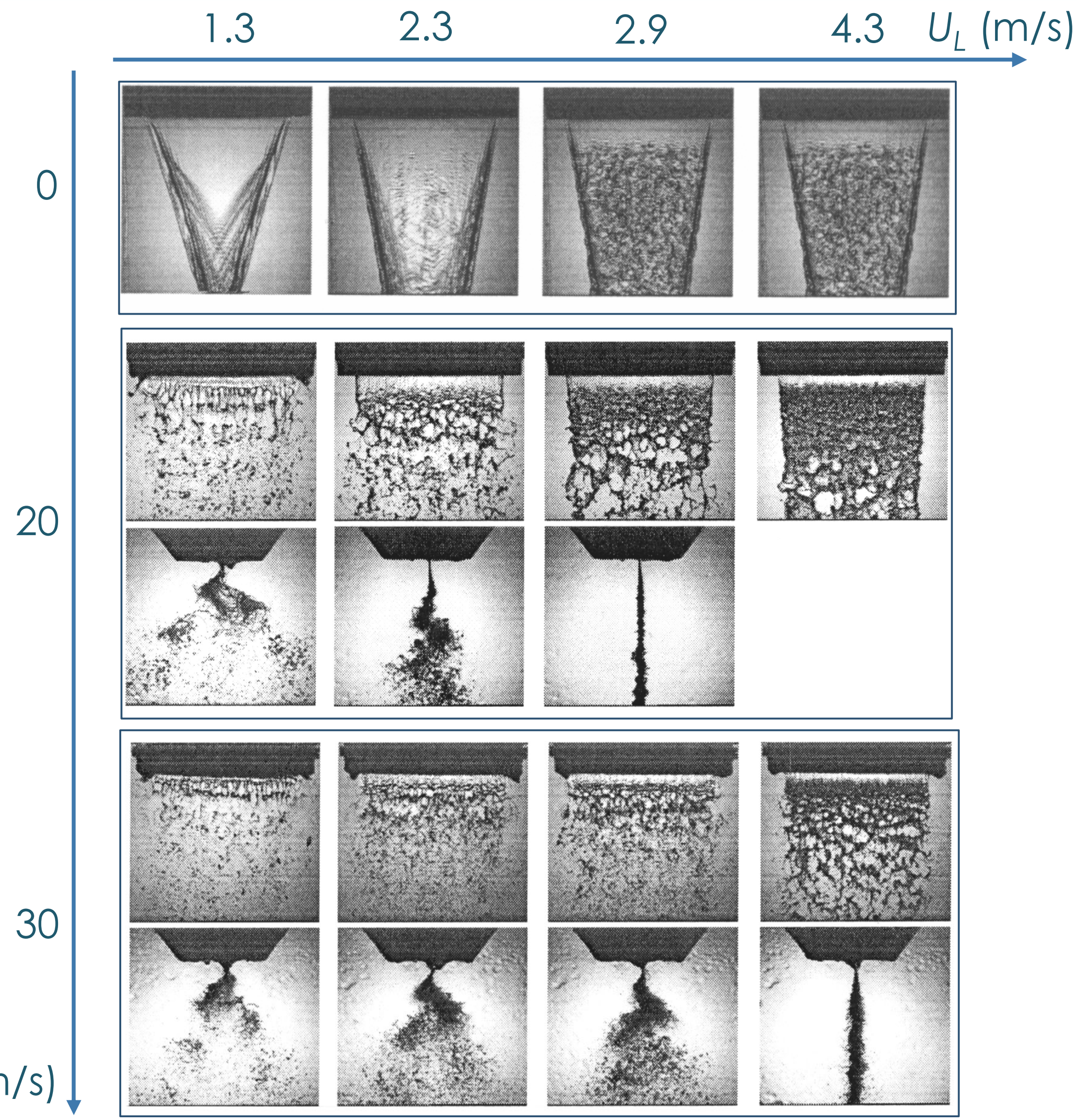


$$Oh = \frac{\sqrt{We_L}}{Re} = \frac{\mu_L}{\sqrt{\rho_L \sigma d}}$$

Photos CORIA

Air assisted Atomization

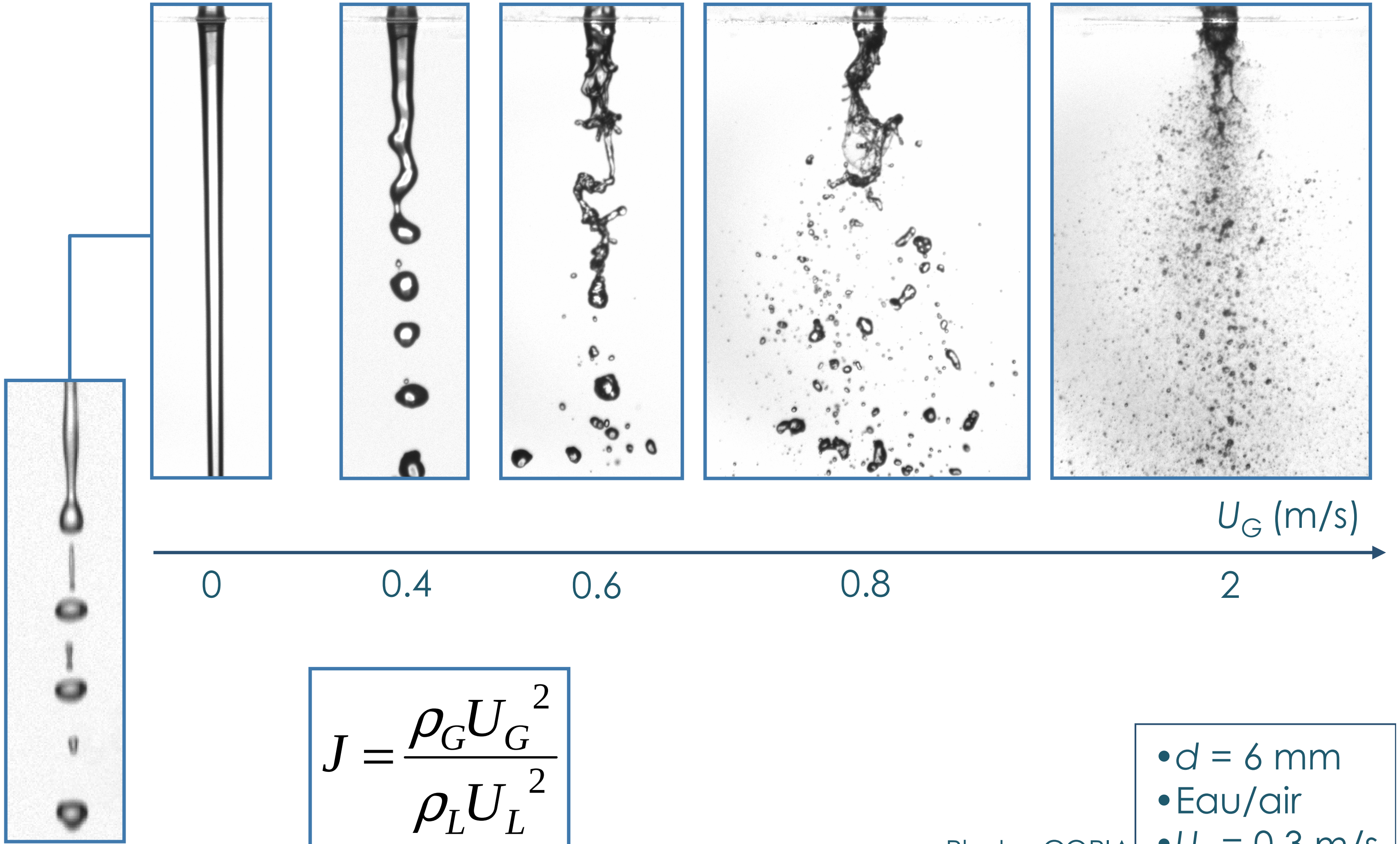
$$J = \frac{\rho_G U_G^{\;2}}{\rho_L U_L^{\;2}}$$



Photos : Carvalho, Heitor and Santos (1998)

- Liquid thickness :e= 0.7 mm
- L/e= 114
- e_G: 7 mm
- Water/air

Air assisted atomization (Co-axial jets)



$$J = \frac{\rho_G U_G^{\;2}}{\rho_L U_L^{\;2}}$$

Photos CORIA

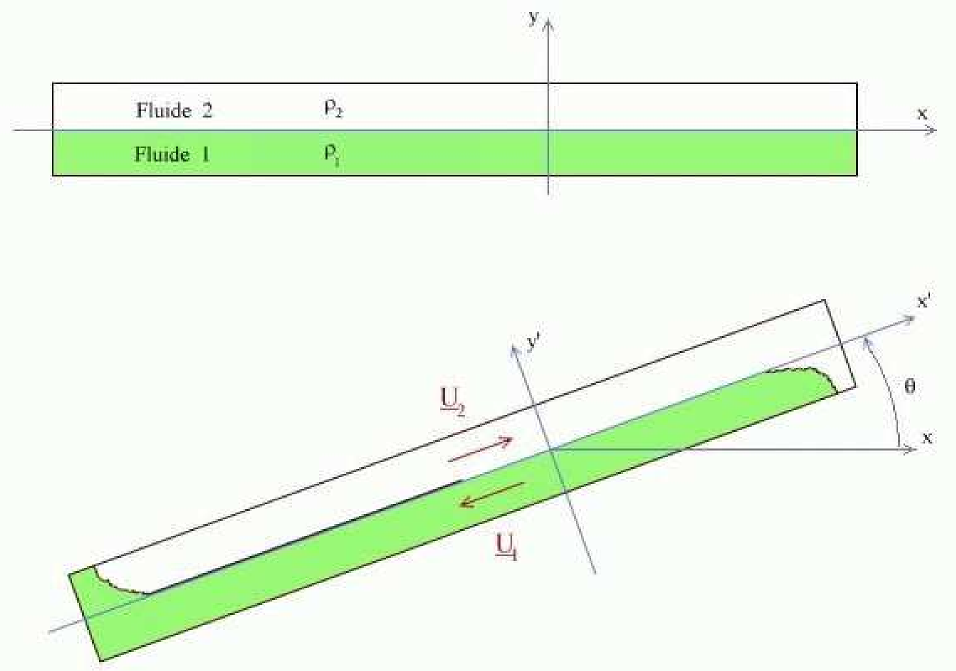
- d = 6 mm
- Eau/air
- U_L = 0.3 m/s

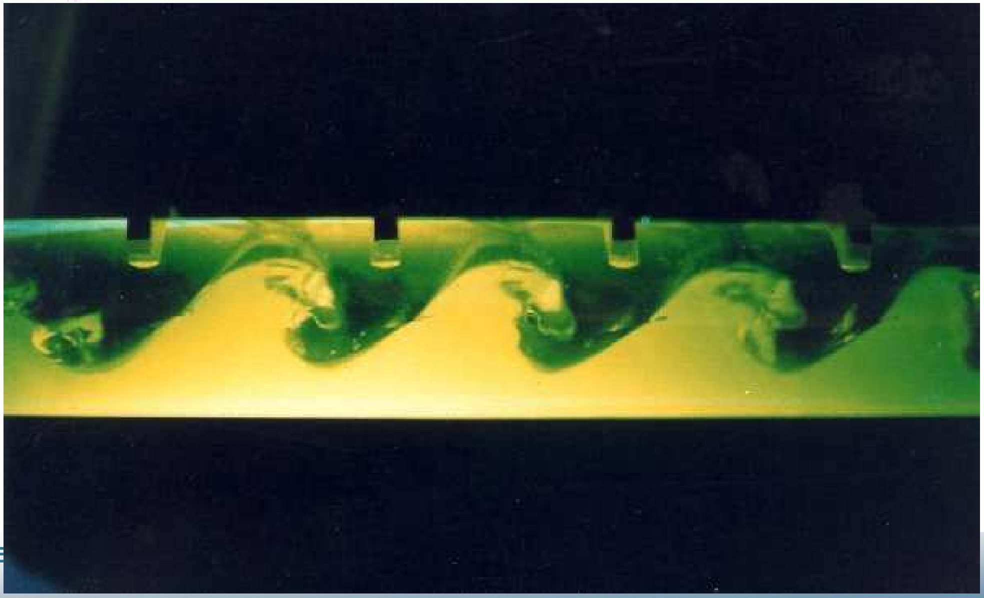
C. Dumouchel, Heat and mass transfer in spray systems, 2005

Basic phenomena:

Linear instabilities

Kelvin – Helmholtz instability

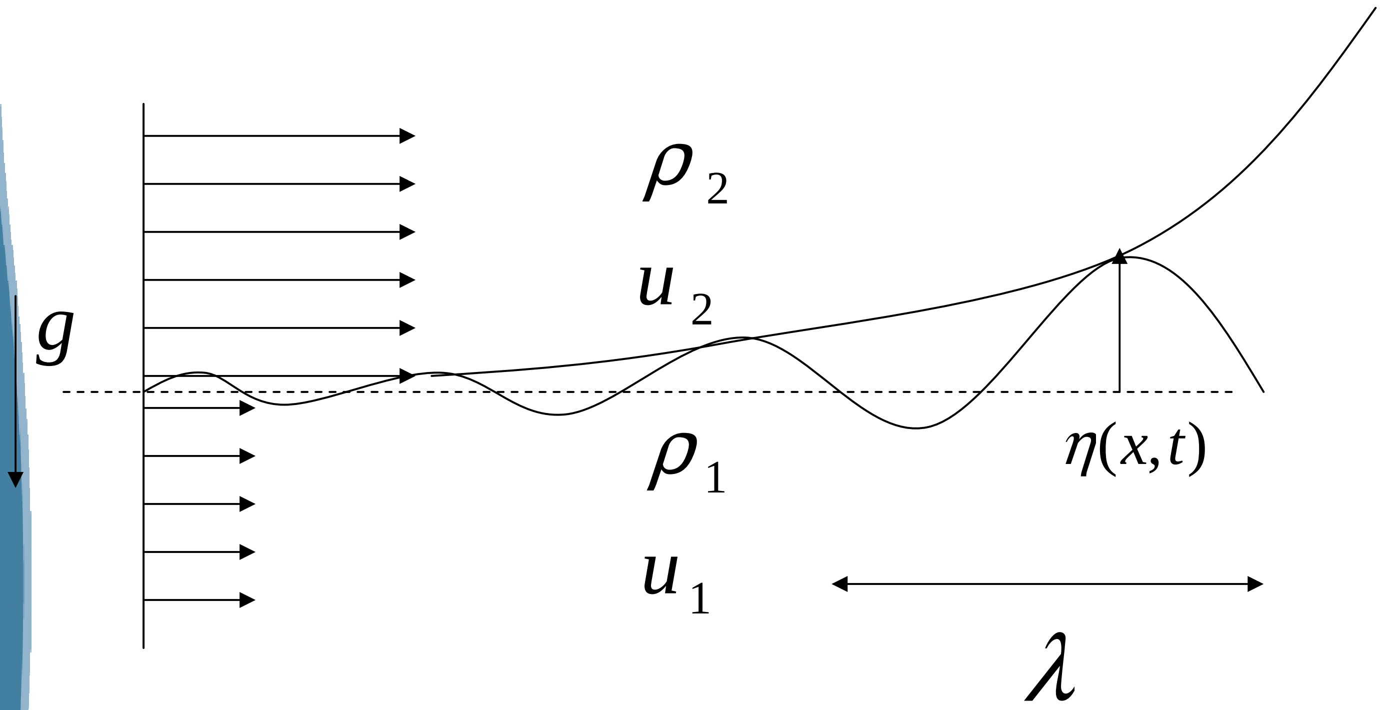




Kelvin – Helmholtz instability

Main results:

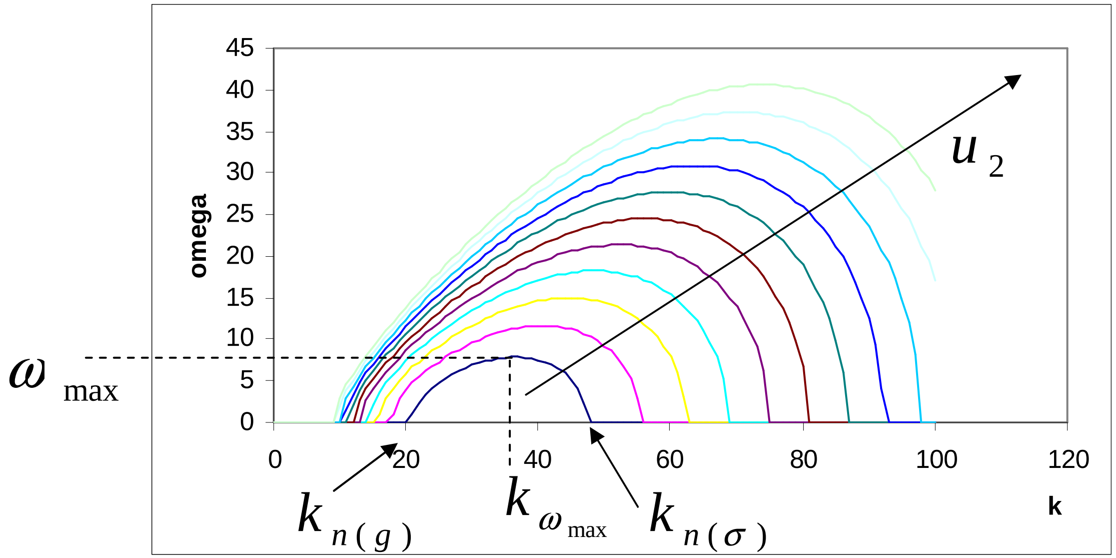
$$\eta(x,t) = \eta_0 e^{\omega t}$$



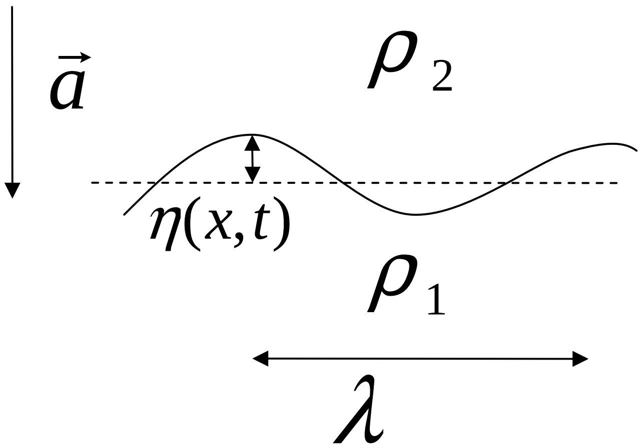
$$p_{s1} - p_{s2} = \sigma \underline{\nabla} \bullet \underline{n}_{12}$$

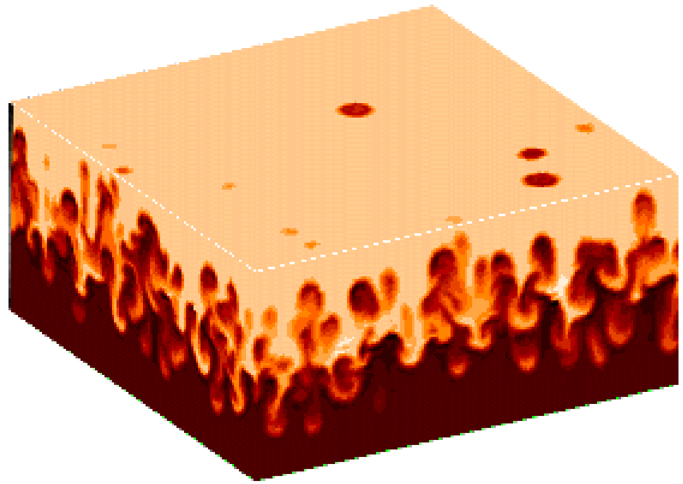
Dispersion equation: $\boxed{\omega = f\left(k = \frac{2\pi}{\lambda}\right)}$

Dispersion diagram: Kelvin – Helmholtz instability

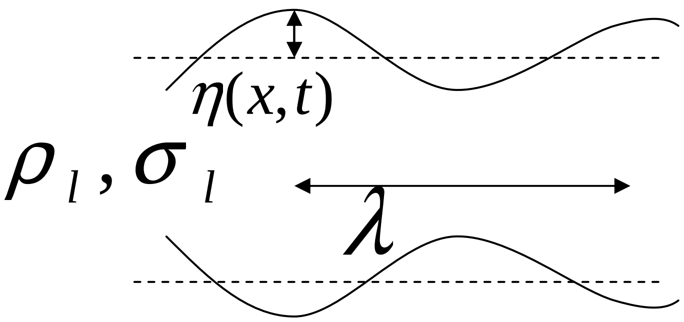


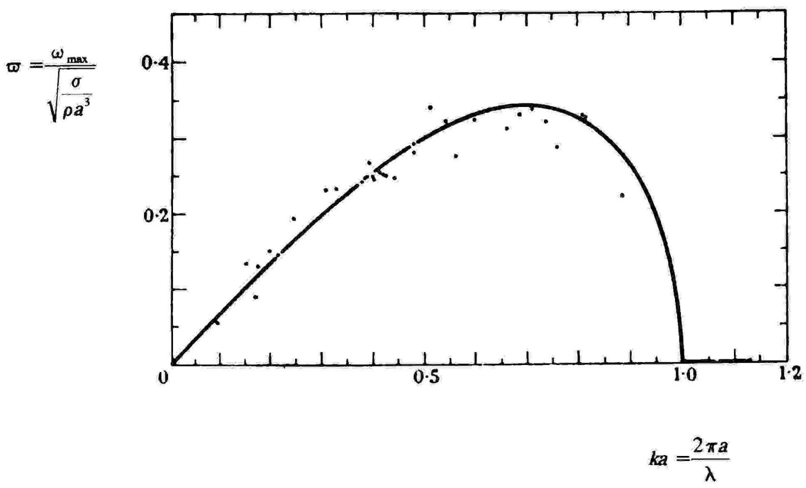
Rayleigh-Taylor instability

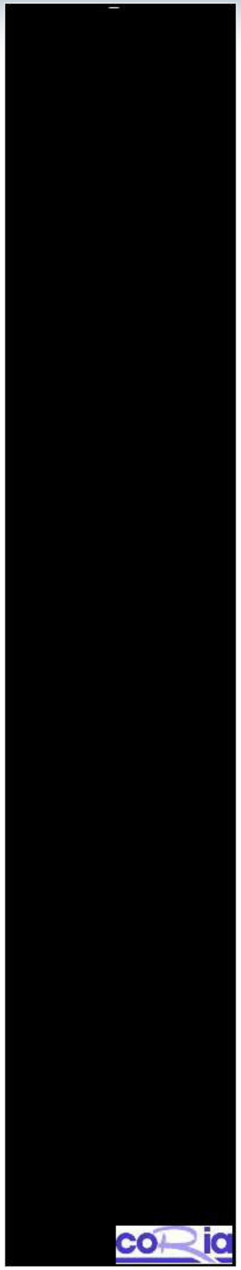




Rayleigh-Plateau instability

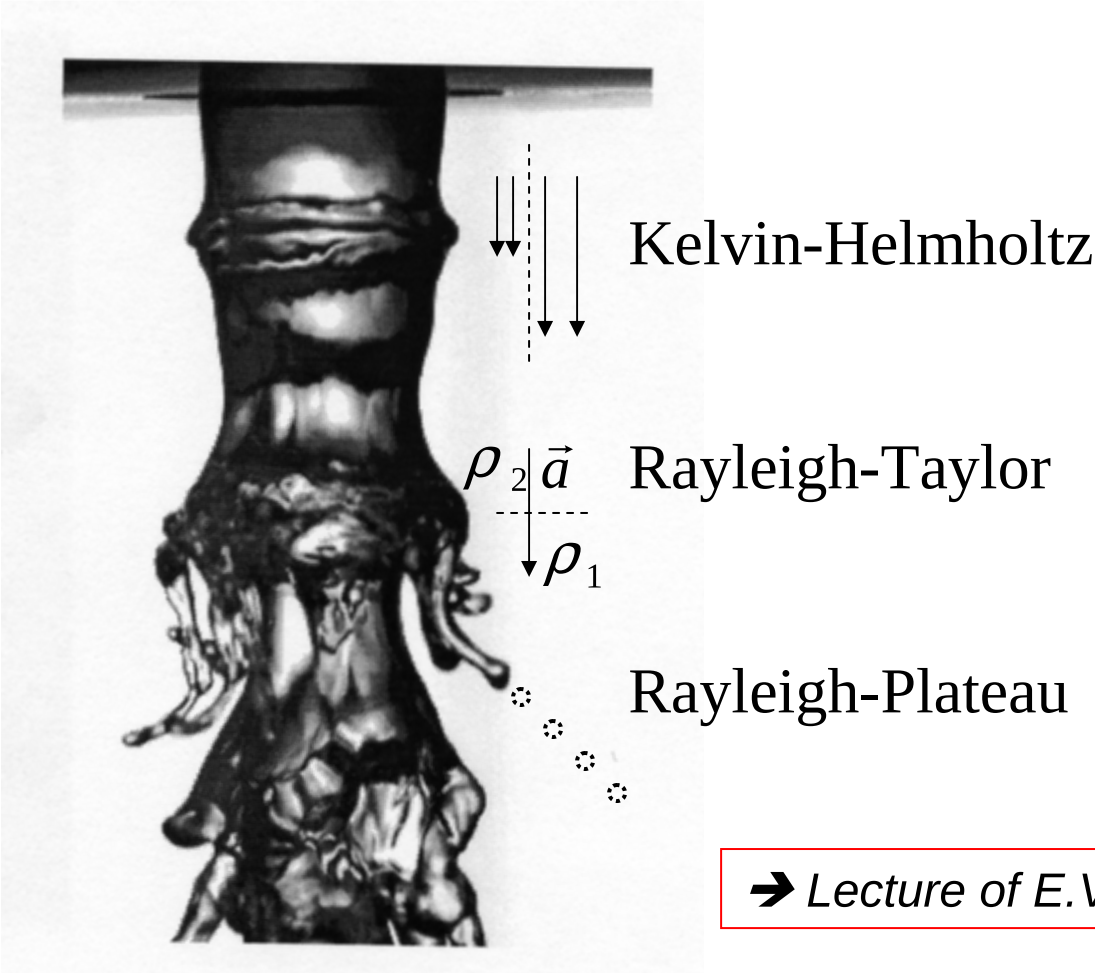






➔To understand physical phenomena

➔To give an explanation of droplet formation



➔ *Lecture of E.Villermaux next week*

P. H. Marmottant and E. Villermaux, Journal of Fluid Mechanics ***498*** *(498), 73 (2004)*

➔ But not always so clear ?

$u_g(m/s)$	$u_l = 0.33m/s$	$u_l = 0.58m/s$	$u_g(m/s)$
15.75			21.7
21.7			40.6
28			56
40.6			85

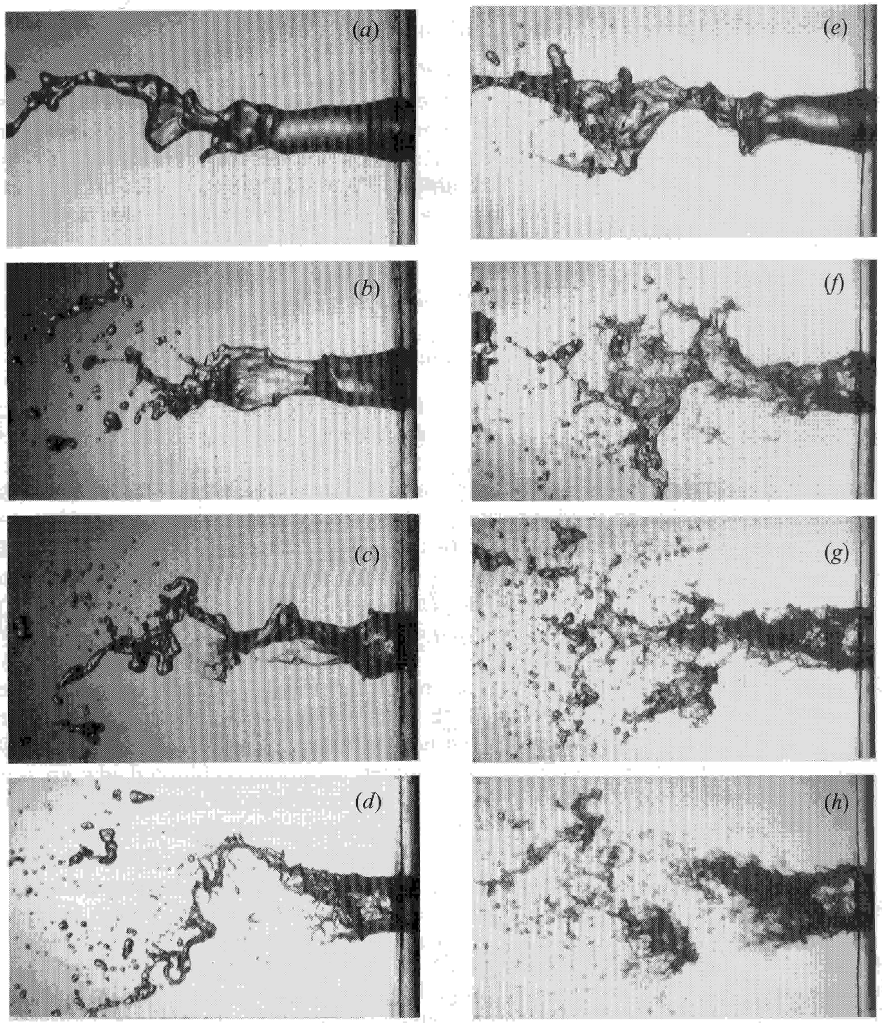


FIGURE 2. Instantaneous flow visualization of the break-up of the liquid jet by the annular air jet. (*a*) $U_g = 15.75$ m s^{-1}, $M = 3.8$, $We_0 = 16$, $Re_l = 830$; (*b*) $U_g = 21.7$ m s^{-1}, $M = 7.35$, $We_0 = 31$, $Re_l = 1120$; (*c*) $U_g = 28$ m s^{-1}, $M = 12.2$, $We_0 = 52$, $Re_l = 1450$; (*d*) $U_g = 40.6$ m s^{-1}, $M = 25$, $W_0 = 110$, $Re_l = 2100$; (*e*) $U_g = 21.7$ m s^{-1}, $M = 2.05$, $We_0 = 31$, $Re_l = 1120$; (*f*) $U_g = 40.6$ m s^{-1}, $M = 7.0$, $We_0 = 110$, $Re_l = 2100$; (*g*) $U_g = 56$ m s^{-1}, $M = 13$, $We_0 = 210$, $Re_l = 2900$; (*h*) $U_g = 85.4$ m s^{-1}, $M = 31$, $We_0 = 489$, $Re_l = 4420$.

Two-phase flows:

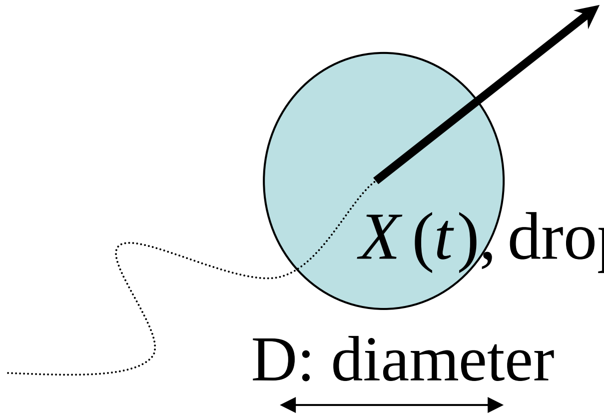
Main formalisms

Generally based on dispersed phase (at less discrete)

➔A carrier phase can be defined, ex: GAS

➔Transported discrete particles, ex: DROPLET

➔Few parameters are involved:



But also:

- **Droplet** temperature, concentration, departure to sphericity, …
- **Gas characteristics seen** by droplet: velocity, temperature, concentration,…

Statistical description:

Joint distribution of drop characteristic➔ *f(X_E ,t ,D ,u ,T, …)*

Boltzmann-Williams equation:

$$\frac{\partial f}{\partial t}+\frac{\partial \dot{x}_i f}{\partial x_i}+\frac{\partial \dot{u}_i f}{\partial u_i}+\frac{\partial \dot{D} f}{\partial r}+\frac{\partial \dot{T} f}{\partial T}=\Gamma$$

$$\frac{\partial \dot{A} f(x_i,t,u_i,D,T)}{\partial A}\Rightarrow \dot{A}=\left\langle \dot{A}(x_i,t,u_i,D,T,u_{i,g},T_g,\ldots)\right\rangle\Big|_{x_i,t,u_i,D,T}$$

Position: $\dot{x}_i=u_i$

Evaporation (D^2 law) :

$$\dot{D}=\left\langle \dot{D}(x_i,t,u_i,D,T,u_{i,g},T_g,\ldots)\right\rangle\Big|_{x_i,t,u_i,D,T}$$

$$\dot{D}=\left\langle \frac{\rho_g}{\rho_l r} D_v Sh(\mathrm{Re}_d=\frac{2r\left\|\vec{u}-\vec{u}_g\right\|}{\nu_g},S_c)\ln\left(\frac{1-Y_v}{1-Y_{vs}}\right)\right\rangle\Big|_{x_i,t,u_i,r,T}$$

Many methods: focus on the diameter distribution

Models for droplet

Mass transfer

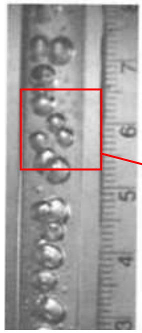
drag

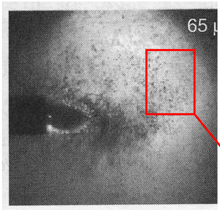
Secondary breakup

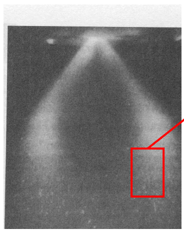
Heat transfer

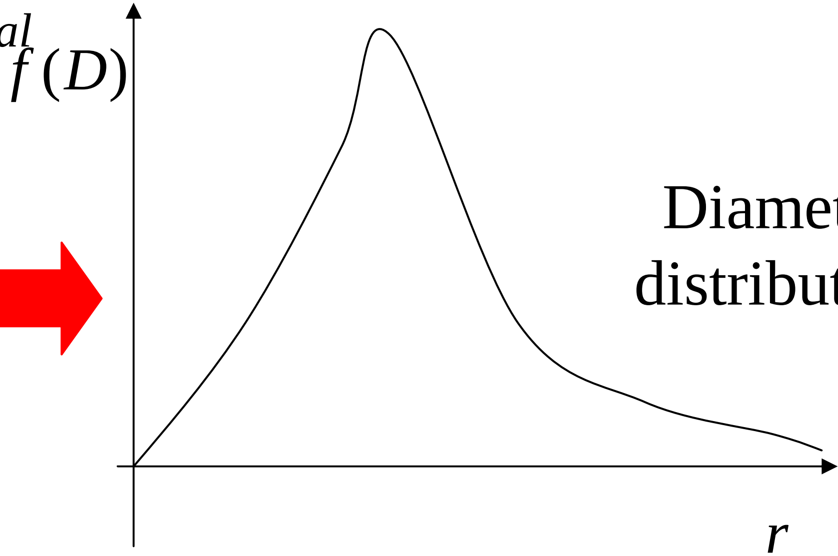
Boltzman-Williams Equation

$$f(\vec{x}, t, \vec{u}, r, T, \ldots)$$









Diameter distribution

Lagrangian Models:
Direct resolution of the B.-Williams equation

Monte-Carlo approach: a set of sample (droplet) is followed

For each droplet, characteristic evolution is solved (Lagrangian)

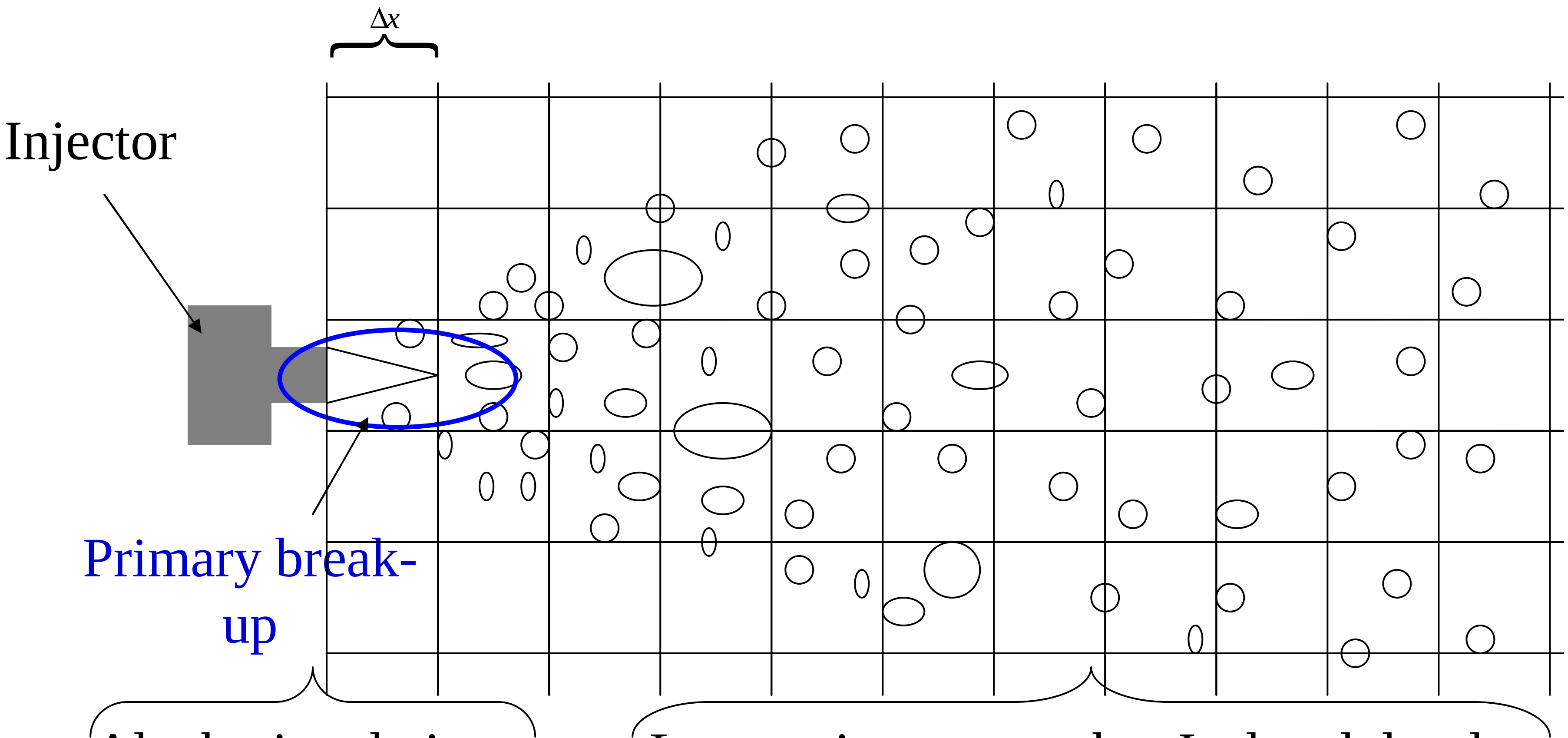
$$\begin{cases} \dfrac{dx_i}{dt} = \dot{x}_i = u_i \\ \dot{u}_i = drag + gravity + \ldots \\ \dot{D} = breakup + evaporation + \ldots \\ \dot{T} = heat\,transfer \end{cases}$$

Statistic are obtained by summing over droplet samples

« Lagrangian Method »,« DDM Dispersed Droplet Model »

Dukowicz$_{1980}$

Application to atomization ➔ **Lagrangian Methods**



Algebraic relations

➔Initial Diameters

➔Initial velocities

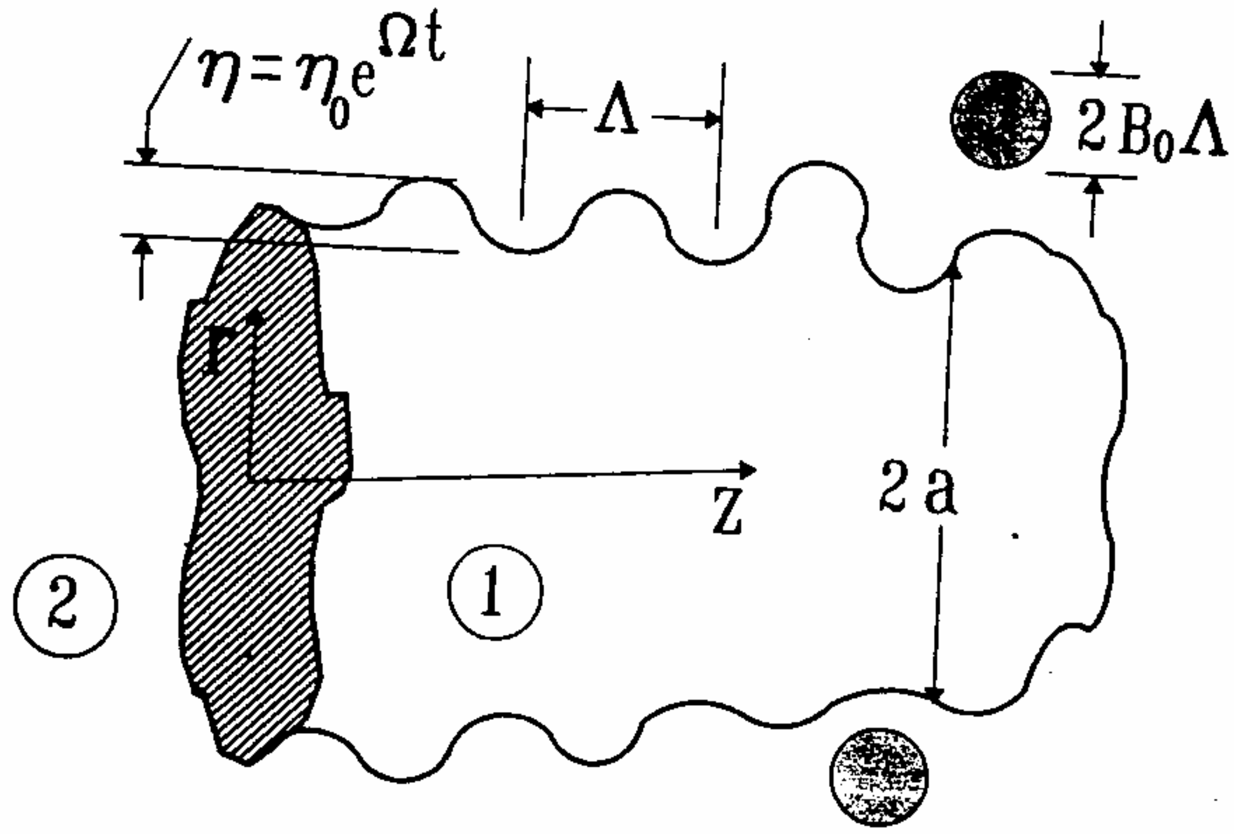
Lagrangian approach ~ Isolated droplets

Drag, Turbulent dispersion, vaporization and combustion

Lagrangian Models: Primary Atomization

Reitz model *(A&S 1987)* or « Wave model » :

Surface instability :Kelvin –Helmholtz



Kelvin-Helmholtz, Wave model *(R. Reitz, A&S 1987)*

Spay angle: $tg\left(\frac{\theta}{2}\right) = A_1 \Lambda \Omega u_0$

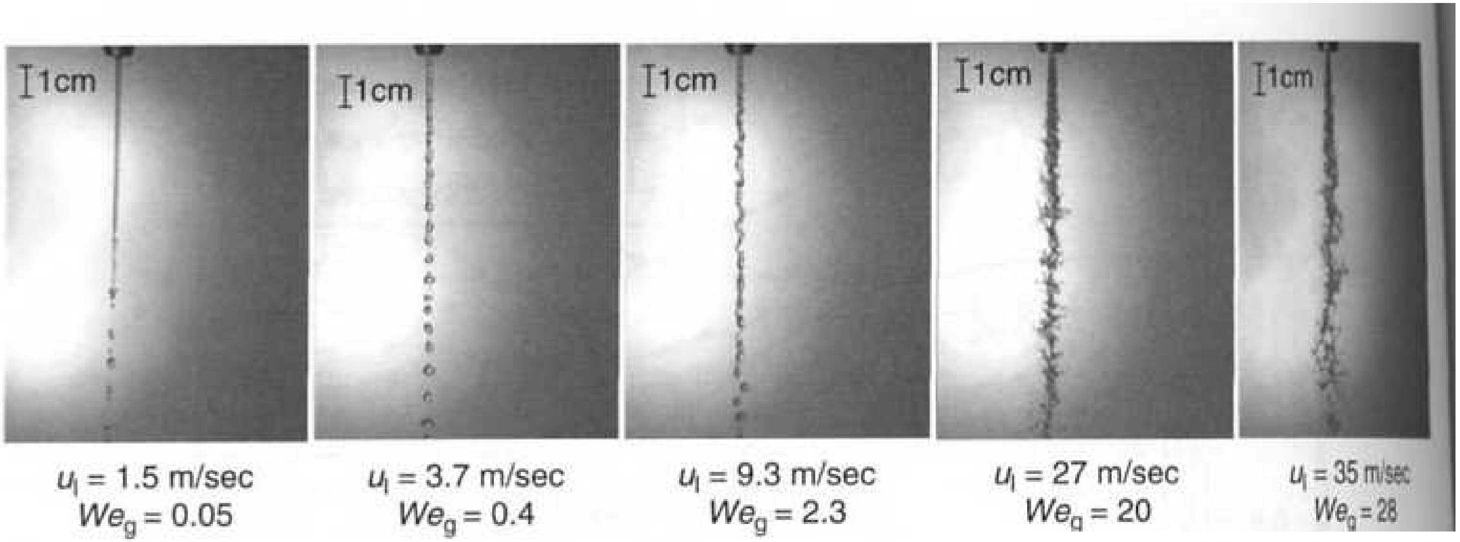
Bulk velocity: $u_0 = c\left(2\Delta p / \rho_l\right)$, c :discharge coefficient

Break-up: parent drop radius a and child drop radius r

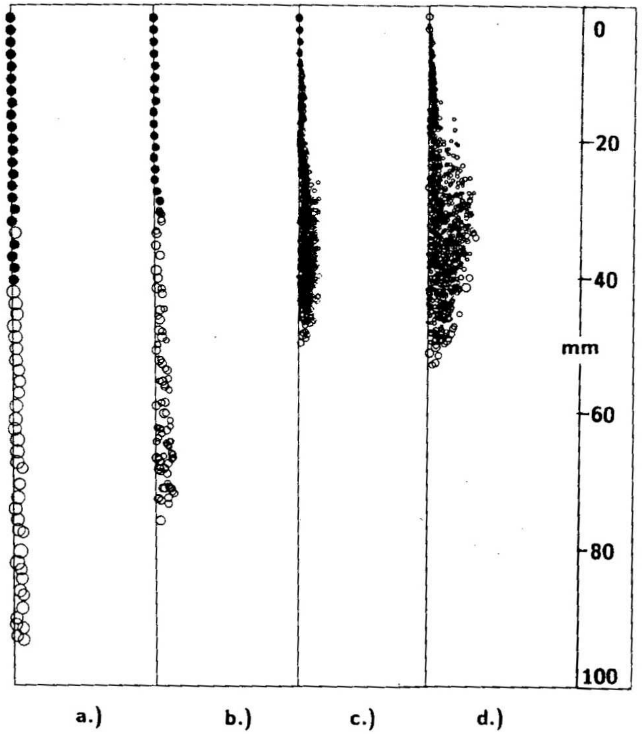
$$\frac{da}{dt} = -\frac{(a-r)}{\tau} \quad \text{with} \quad \tau = 3.726\, B_1 \frac{a}{\Lambda\Omega}$$

$$r = \begin{cases} B_0 \Lambda & \text{if } B_0\Lambda \le a \\ \min\left[\left(\dfrac{3\pi a^2 u_l}{2\Omega}\right)^{1/3} ; \left(\dfrac{3a^2\Lambda}{4}\right)^{1/3}\right] & \text{if } B_0\Lambda > a \text{, only one time} \end{cases}$$

Results/ Experiment



Multiphase flow handbook, edited by Clayton T. Crowe, Taylor&Francis

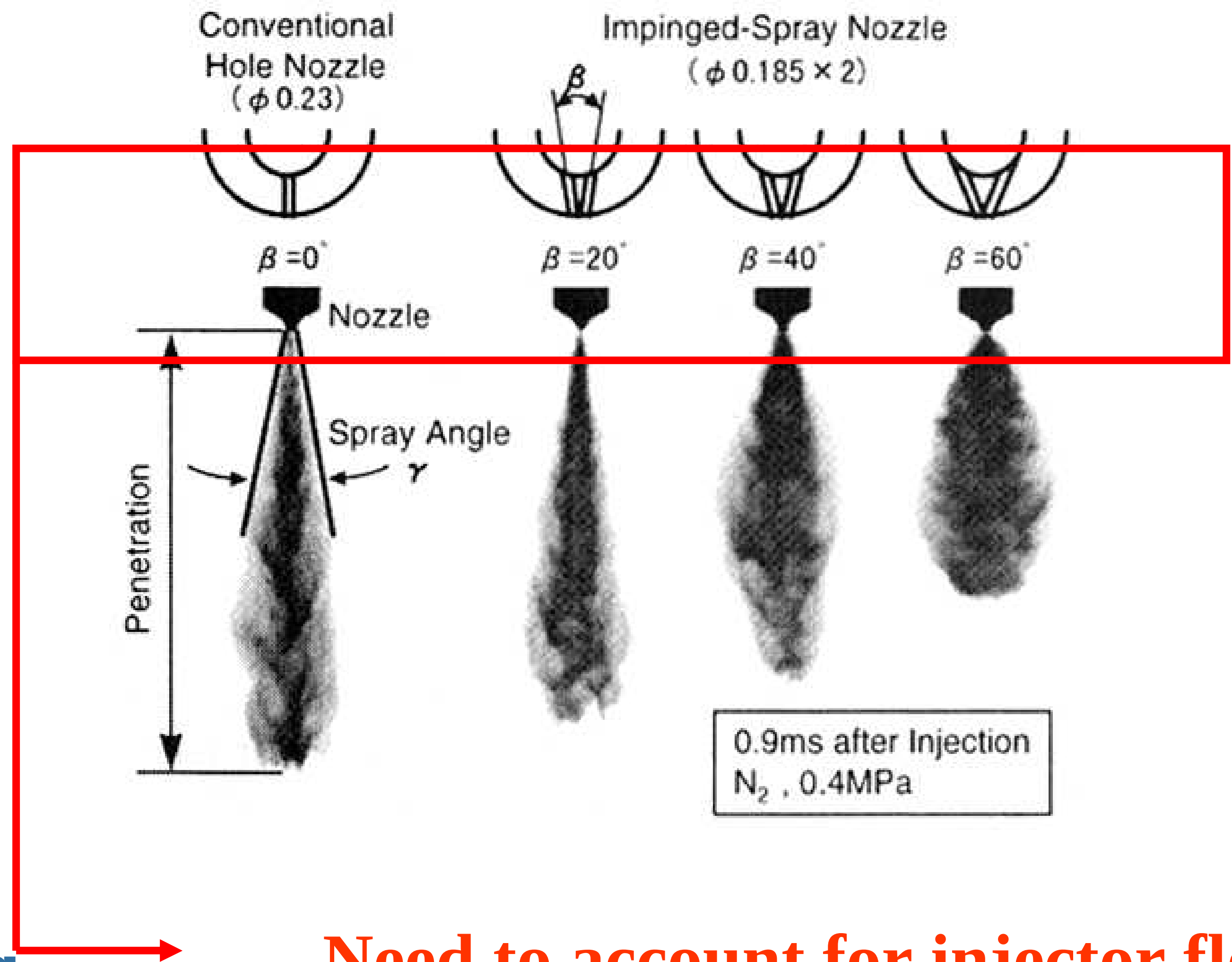


Kelvin-Helmotz, model Wave (R. Reitz, A&S 1987)

Weg= 4.5 ; 18.1; 45; 226

It works …, but "constants" are dependent of the injector.

How to take into account complicated injector geometry ?



Yoshinori Iwabuchi et al (SAE 1999-01-0185)

Need to account for injector flow

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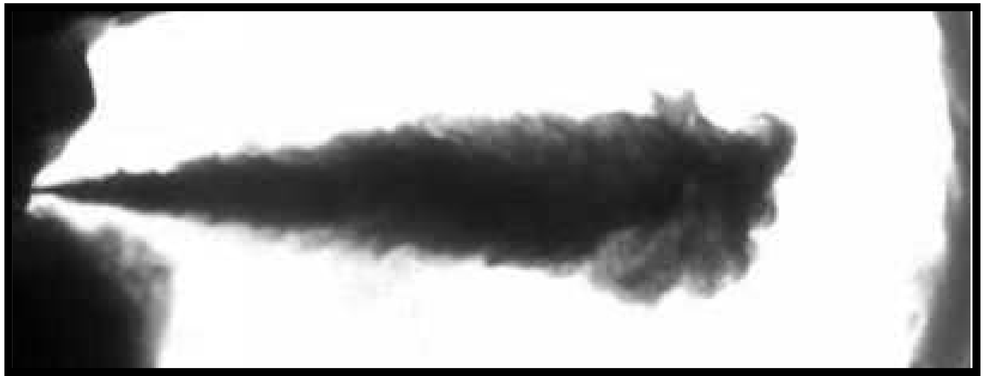
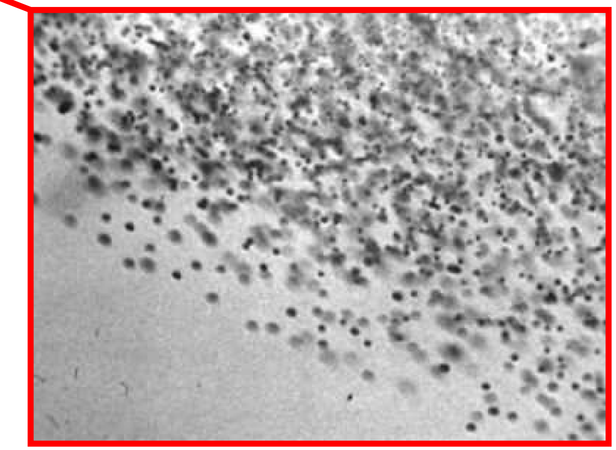
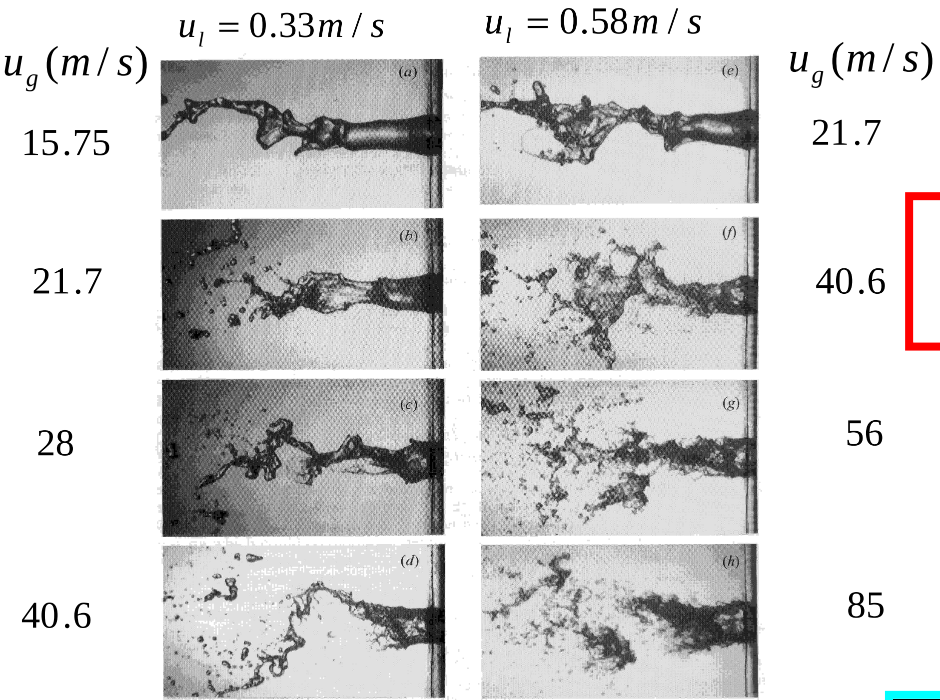




Part III : Turbulence, droplet, vaporization, mixing and combustion

ELSA model

Eulerian Lagrangian Spray Atomisation



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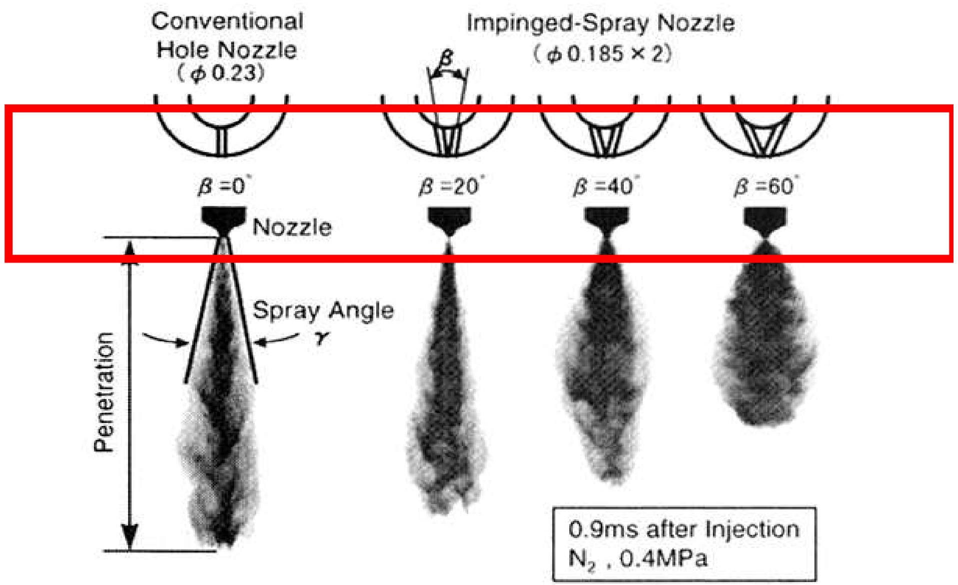
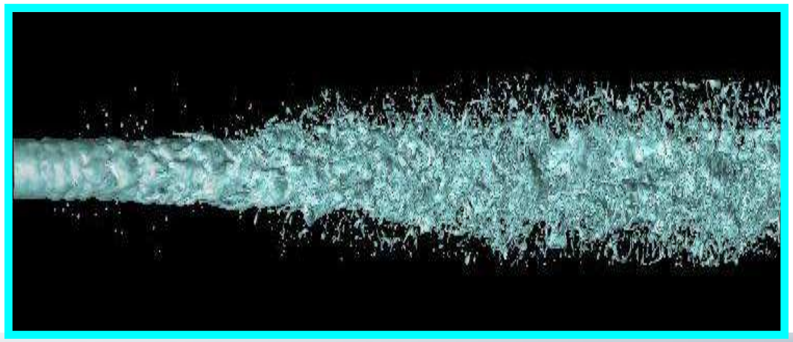
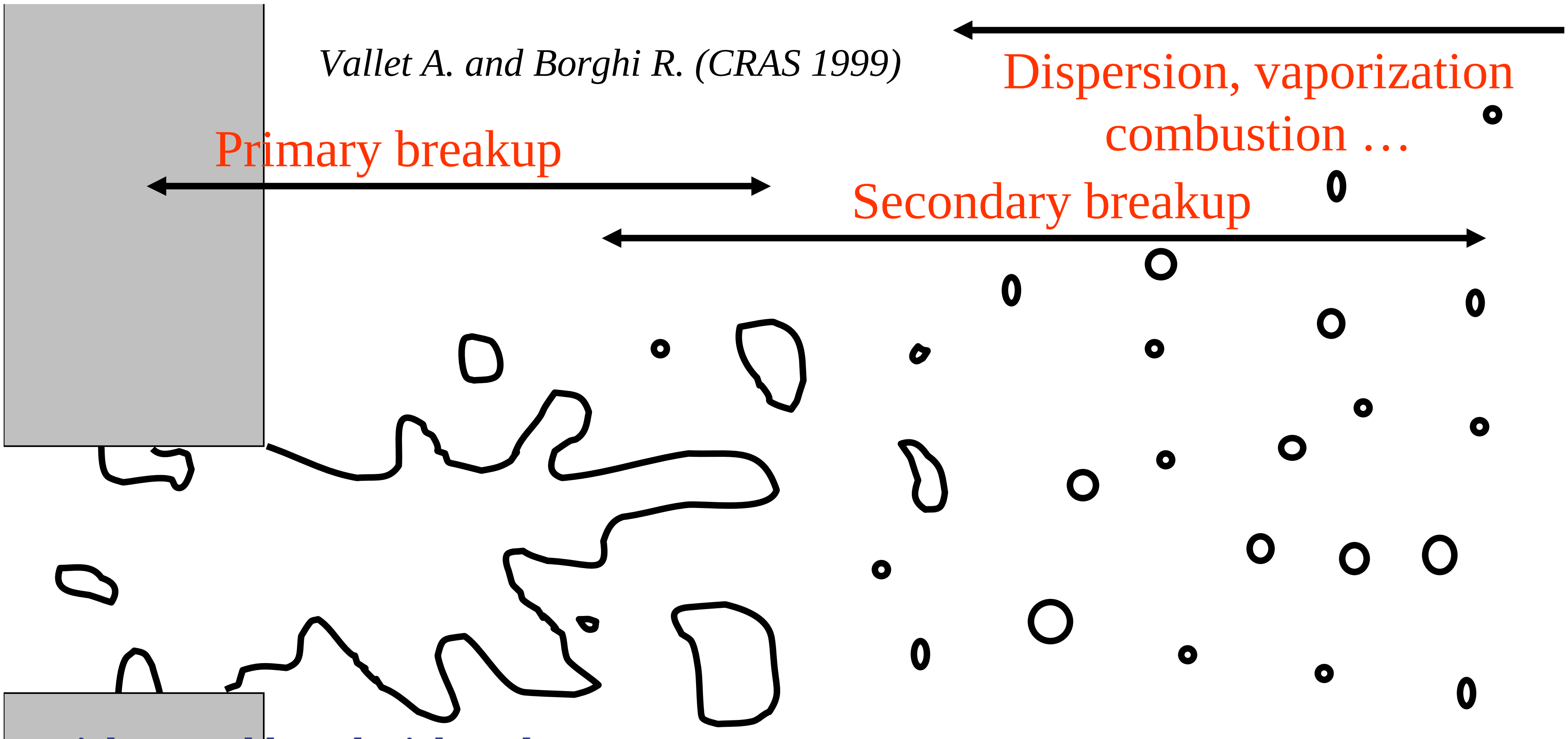






High Reynolds and High Weber:

atomization= turbulent mixing

? Turbulence with high density fluctuation ?

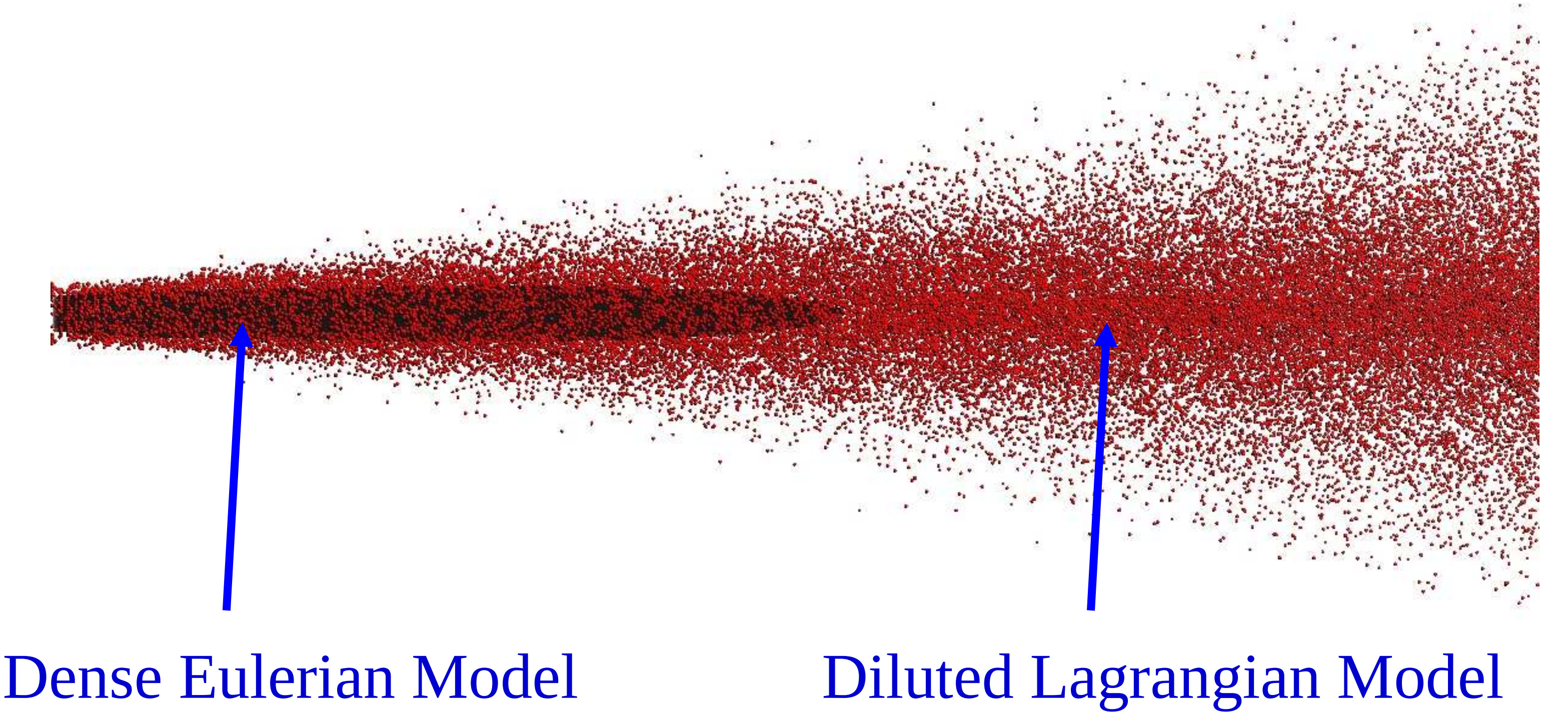
Small scales: effects of molecular viscosity and surface tension

Liquid length scale =>mean droplet size

Eq. of the density of liquid-gas surface

Classical stochastic Lagrangian method

ElSA model in action:



Application to air-blast atomization

Eulerian description of primary break-up mixture flow

A single flow with two species: Gas Y_g and Liquid Y_l

Mean velocity, pressure and density : $\tilde{U}_i, \bar{p}, \bar{\rho}$

Turbulence: $k-\varepsilon$ model or second order models

Transport of the liquid species:

$$\frac{\partial \bar{\rho}\tilde{Y}_l}{\partial t} + \frac{\partial \bar{\rho}\tilde{U}_j\tilde{Y}_l}{\partial x_j} = -\frac{\partial \overline{\rho u_j'' Y_l''}}{\partial x_j}$$

Turbulent liquid mass flux

$$\frac{\partial}{\partial x_j}\bar{\rho}\frac{\nu_t}{D_t}\frac{\partial \tilde{Y}_l}{\partial x_j} \quad ??$$

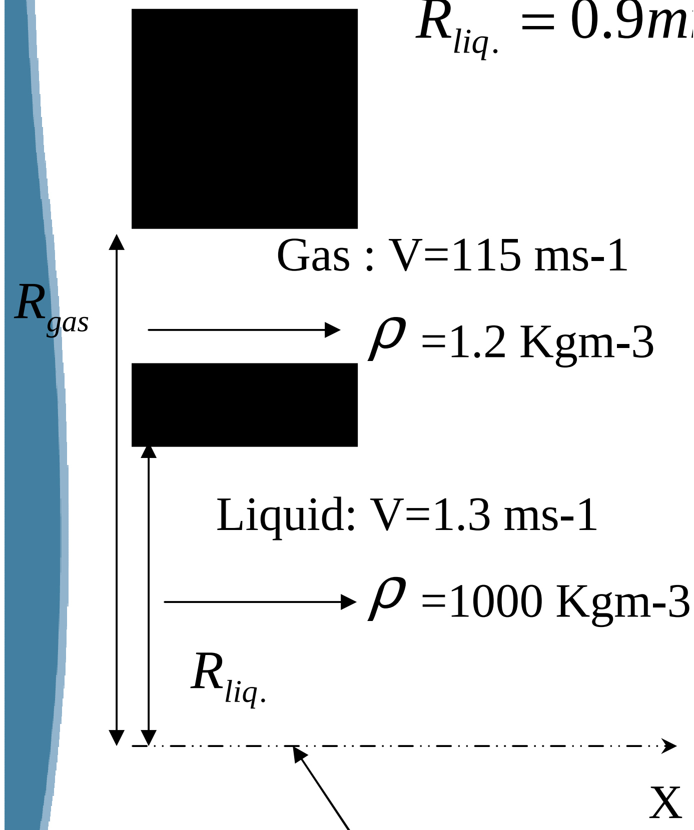
Mean velocity ⇐NOT⇒ Equal velocity: $\boxed{\bar{U}_i\big|_g \neq \bar{U}_i\big|_l}$

$$\boxed{\overline{\rho u_i'' Y_l''} = \bar{\rho}\tilde{Y}_l\tilde{Y}_g(\bar{U}_i\big|_l - \bar{U}_i\big|_g) = \bar{\rho}\tilde{Y}_l(\bar{U}_i\big|_l - \tilde{U}_i)}$$

Modelling turbulence for flows with high density fluctuations

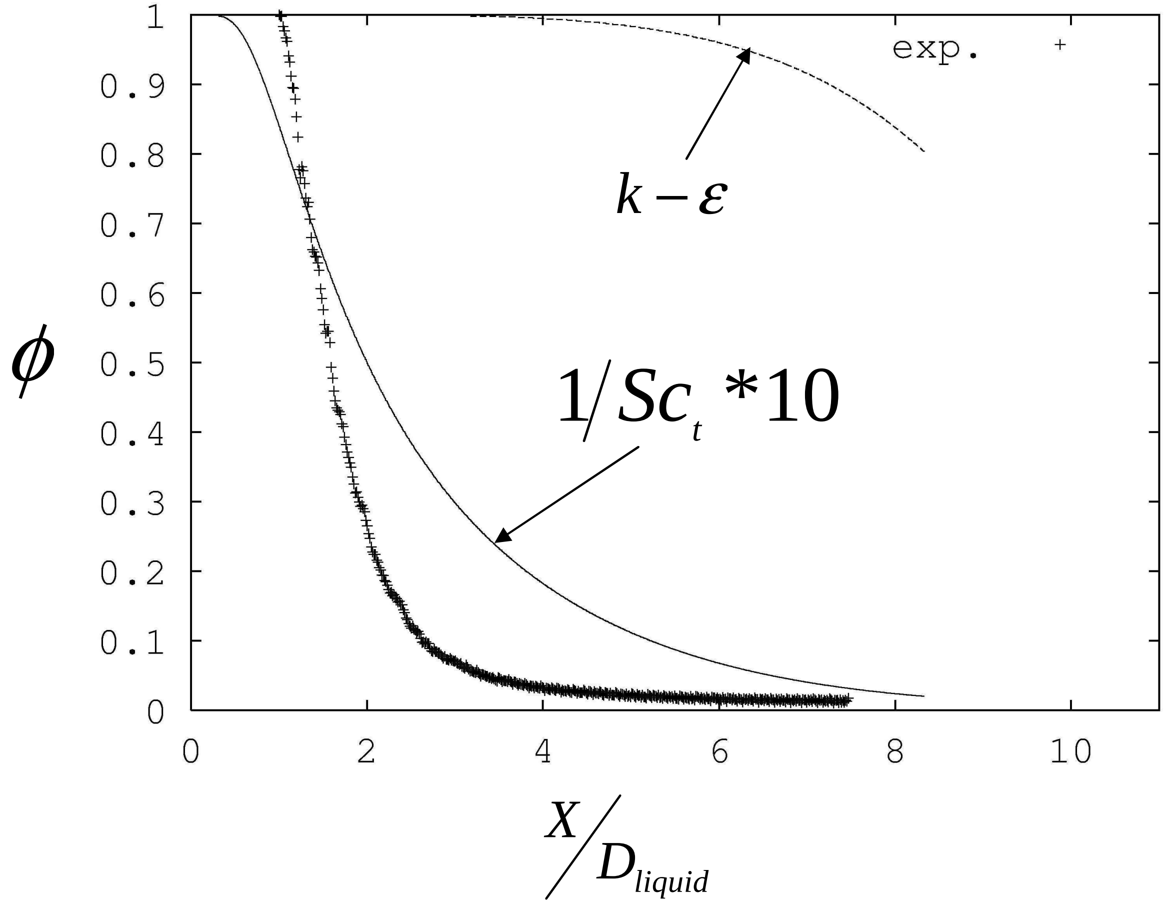
$R_{gaz} = 1.7mm$

$R_{liq.} = 0.9mm$



Symmetry axis

Axial profile of the liquid volume fraction



UMR 6614 CORIA COMPLEXE DE RECHERCHE INTERPROFESSIONNEL EN AEROTHERMOCHIMIE
CNRS – UNIVERSITE et INSA de Rouen

Test case : D.Stepowski et al (Combustion 2002)

Test first and second order model …

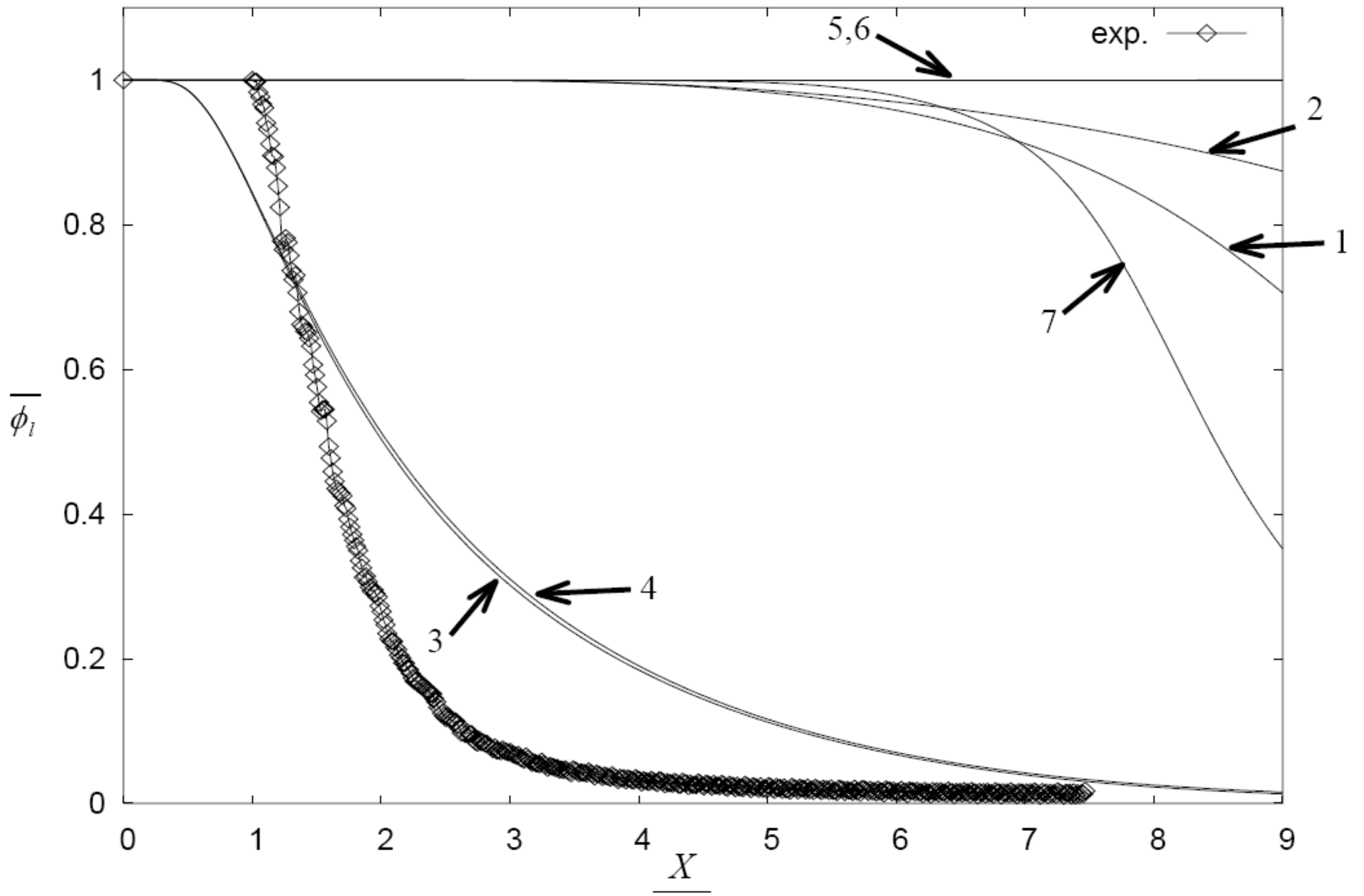


Figure 2: Profiles of the liquid volume fraction along the main axis. The curve with symbols corresponds to experimental data [21]. The regular curves are the result of calculation with: $1 = k - \varepsilon$; $2 = k - \varepsilon + G_k$; $3 = k - \varepsilon, D_t \times 10$; $4 = k - \varepsilon + G_k, D_t \times 10$; $5 = R_{ij} - \varepsilon, R_{iY_l}$; $6 = R_{ij} - \varepsilon + G_{ij}, R_{iY_l} + G_{l_i}$; $7 = R_{ij} - \varepsilon + G_{ij}, D_t$

F.-X. Demoulin et al, Atomization and Sprays, 2007

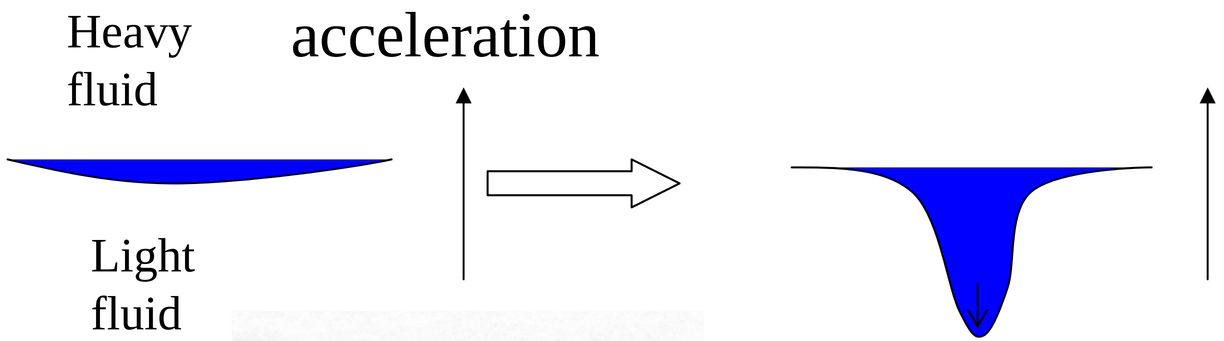
Turbulent modeling of the $\overline{\rho u''_i Y''}$ equation

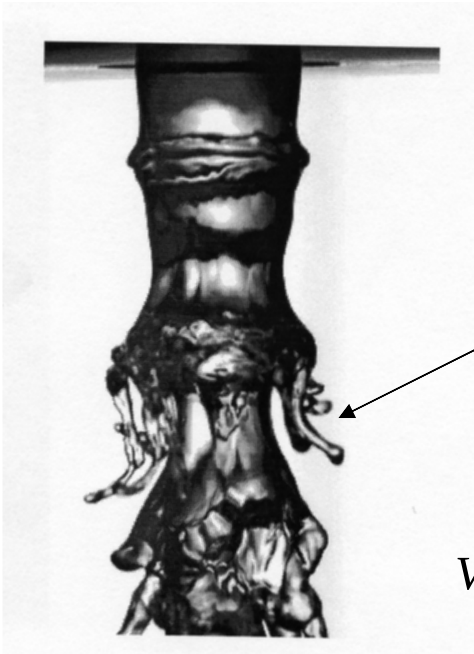
$$\frac{D\overline{\rho v''Y''}}{Dt} = Diff. - \overline{\rho v''v''}\frac{\partial \tilde{Y}}{\partial y} \underbrace{- a_1 \frac{\varepsilon}{k}\overline{\rho v''Y''} + \gamma^{Y} \overline{Y''}\frac{\partial \overline{p}}{\partial x_i}}_{\overline{p'\frac{\partial Y''}{\partial x_i}}} - \overline{Y''}\frac{\partial \overline{p}}{\partial x_i}$$

Classical modeling

$$\boxed{-\overline{\rho v''Y''} = \underbrace{\overline{\rho v''v''}\frac{k}{a_1\varepsilon}}_{\approx \mu_t}\frac{\partial \tilde{Y}}{\partial y}}$$

Rayleigh Taylor Instability



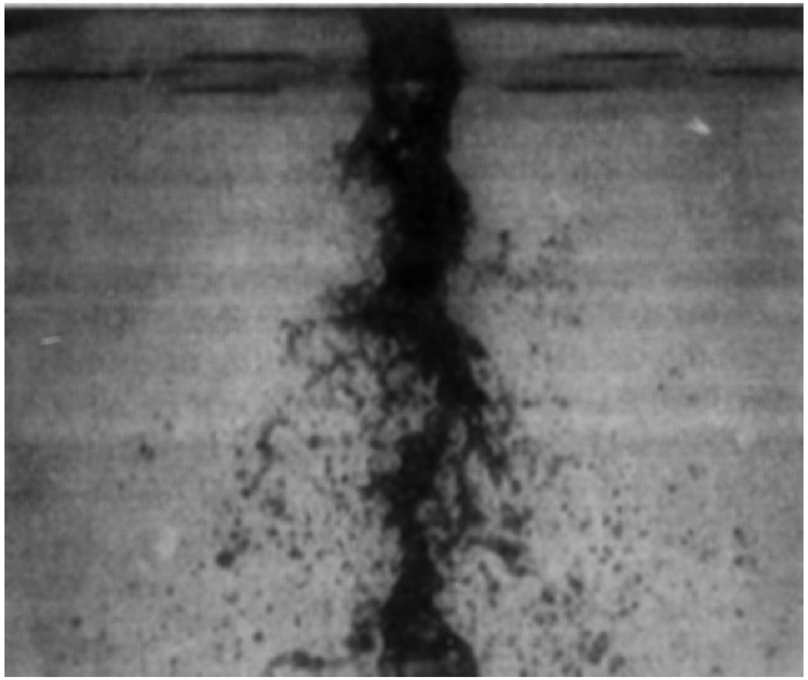


Liquid
ligaments

$\overline{\rho u_i'' Y_l} \nearrow$

Villermaux et al

Turbulent Jet



Hopfinger et al

Not so clear !

Ligaments: Yes

Increase of $\overline{\rho u_i'' Y_l}$: Probable

New modeling of the $\overline{\rho u''_i Y''}$ equation

Increase of turbulent dispersion due to gravity effect

Lumley (1975) and Launder (1975)

$$\overline{p'\frac{\partial Y_l''}{\partial x_i}} = \ldots + C_{y3}\bar{\rho}\left(1/\rho_l - 1/\rho_g\right)\overline{\rho Y_l''Y_l''}g_i$$

New model: replacing gravity by a turbulent acceleration

$$\overline{p'\frac{\partial Y_l''}{\partial x_i}} = \ldots + C_{yr}\left(1/\rho_l - 1/\rho_g\right)\overline{\rho Y_l''Y_l''}\,\overline{\rho v''v''}\frac{\partial \tilde{Y}_l}{\partial x_i}$$

$$\boxed{-\overline{\rho v''Y''} \approx \left(\overline{\rho v''v''}\frac{k}{a_1\varepsilon} + \frac{C_{yr}}{a_1}\frac{k}{\varepsilon}\overline{\rho v''v''}\tilde{Y}(1-\tilde{Y})\left(\frac{\bar{\rho}}{\rho_g} - \frac{\bar{\rho}}{\rho_l}\right)\right)\frac{\partial \tilde{Y}}{\partial y}}$$

Model effect of variable density

Standard model:

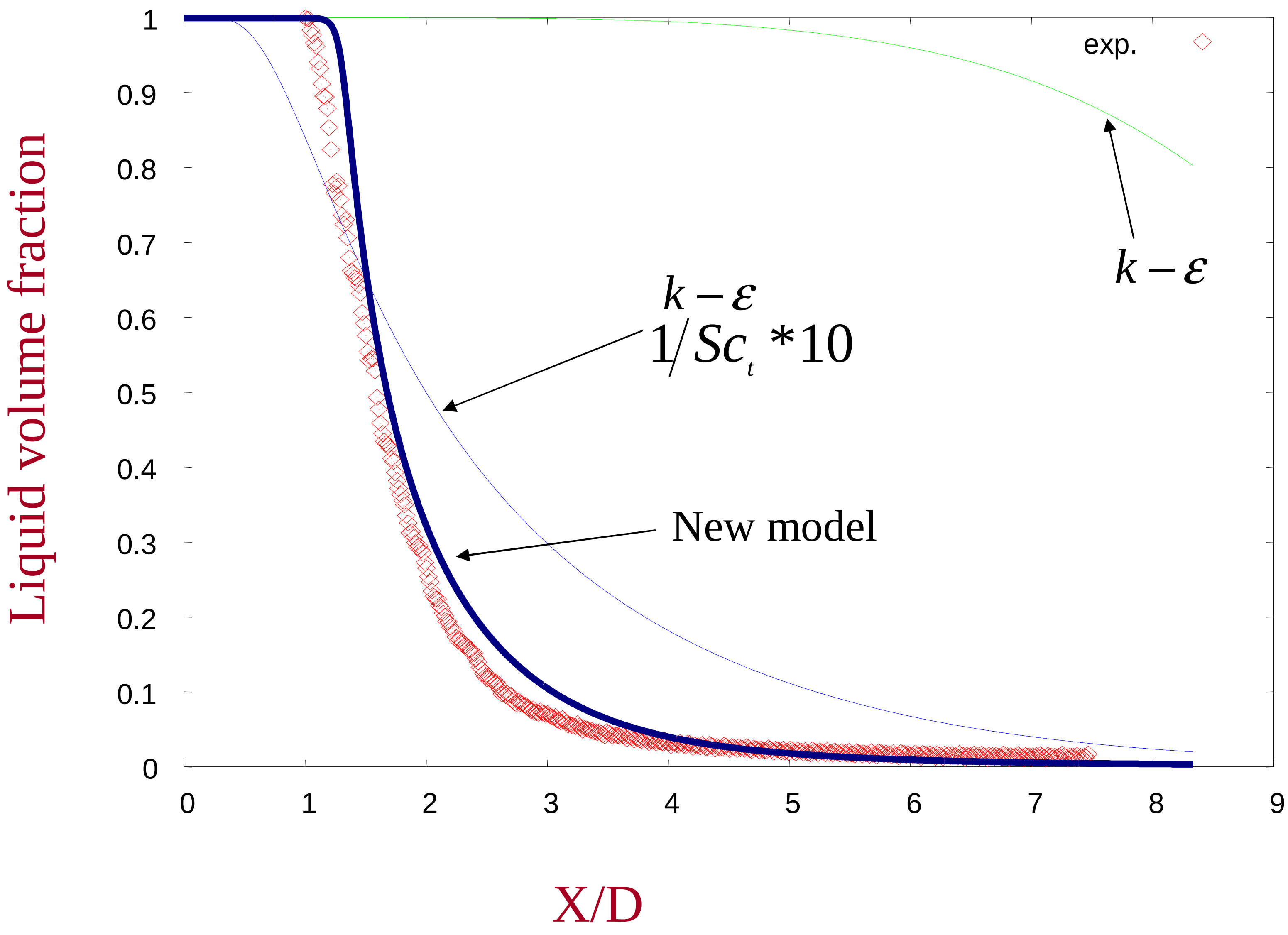
$$\overline{\rho u''_i Y''_l} = -\bar{\rho}\frac{\nu_t}{Sc_t}\frac{\partial \tilde{Y}_l}{\partial x_i}$$

New model: $\overline{\rho u''_i Y''_l}$

$$= -\bar{\rho}\left(\frac{\nu_t}{Sc_t} + C_\rho \frac{k^2}{\varepsilon}\bar{\rho}\left(1/\rho_g - 1/\rho_l\right)\tilde{Y}_l\left(1-\tilde{Y}_l\right)\right)\frac{\partial \tilde{Y}_l}{\partial x_i}$$

$$= -\bar{\rho}\left(\frac{\nu_t}{Sc_t} + C_\rho \frac{k^2}{\varepsilon}\left|\overline{Y''_l}\right|\right)\frac{\partial \tilde{Y}_l}{\partial x_i}$$

Where $\nu_{\mathrm{t}} = c_\mu \frac{k^2}{\varepsilon}, c_\mu = 0.09, Sc_t = 0.9$ and $C_\rho = 1.8$



F.-X. Demoulin et al, Atomization and Sprays, 2007

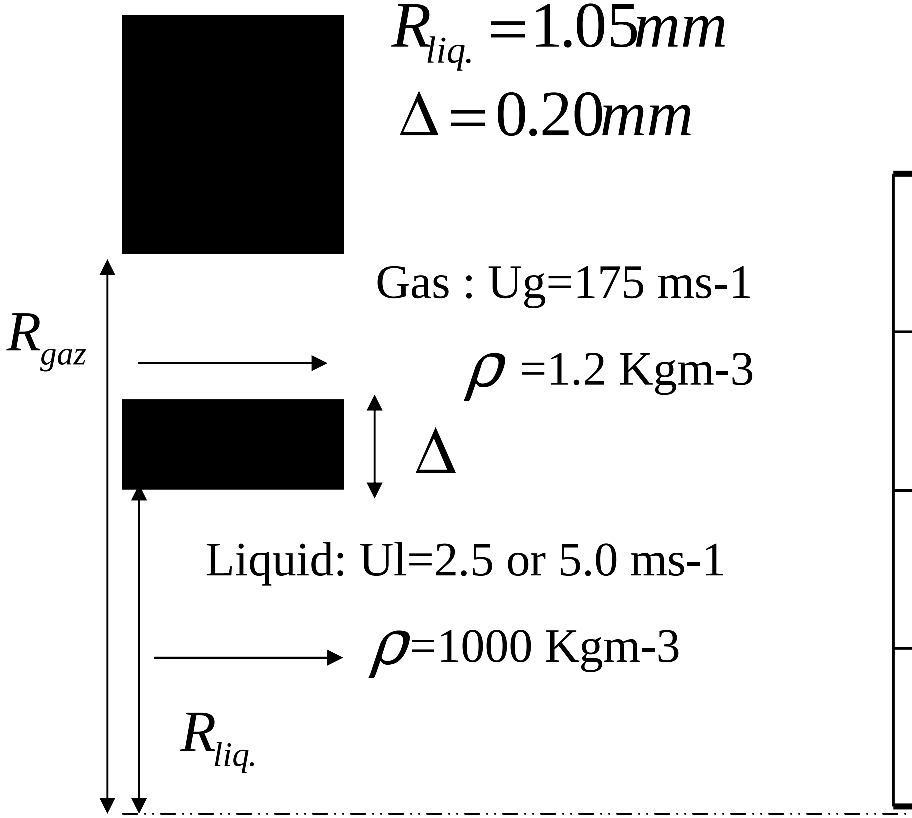
Test of the modeling …

(Carreau et al. 1994)

$$R_{gaz} = 1.8mm$$

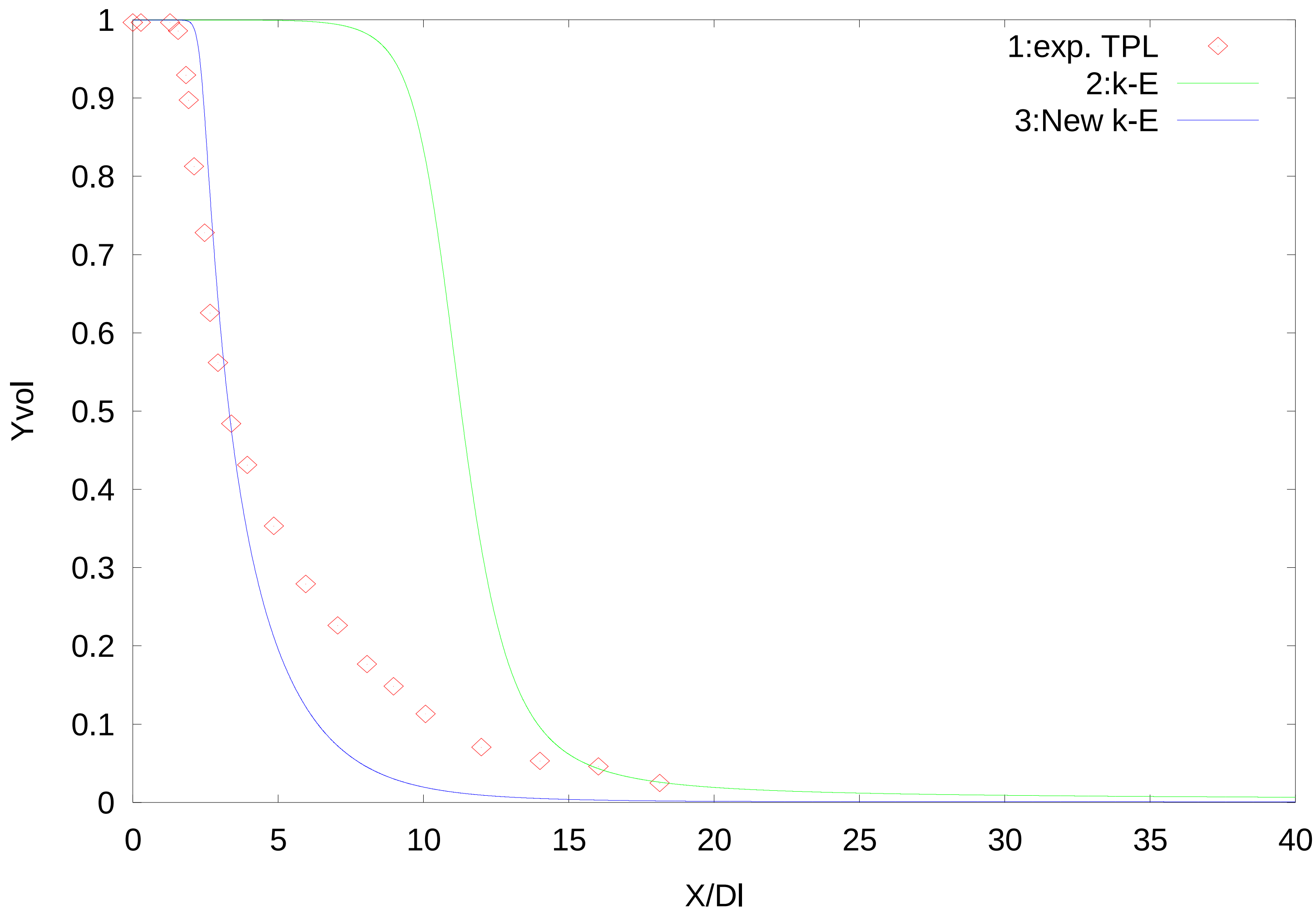
$$R_{liq.} = 1.05mm$$

$$\Delta = 0.20mm$$



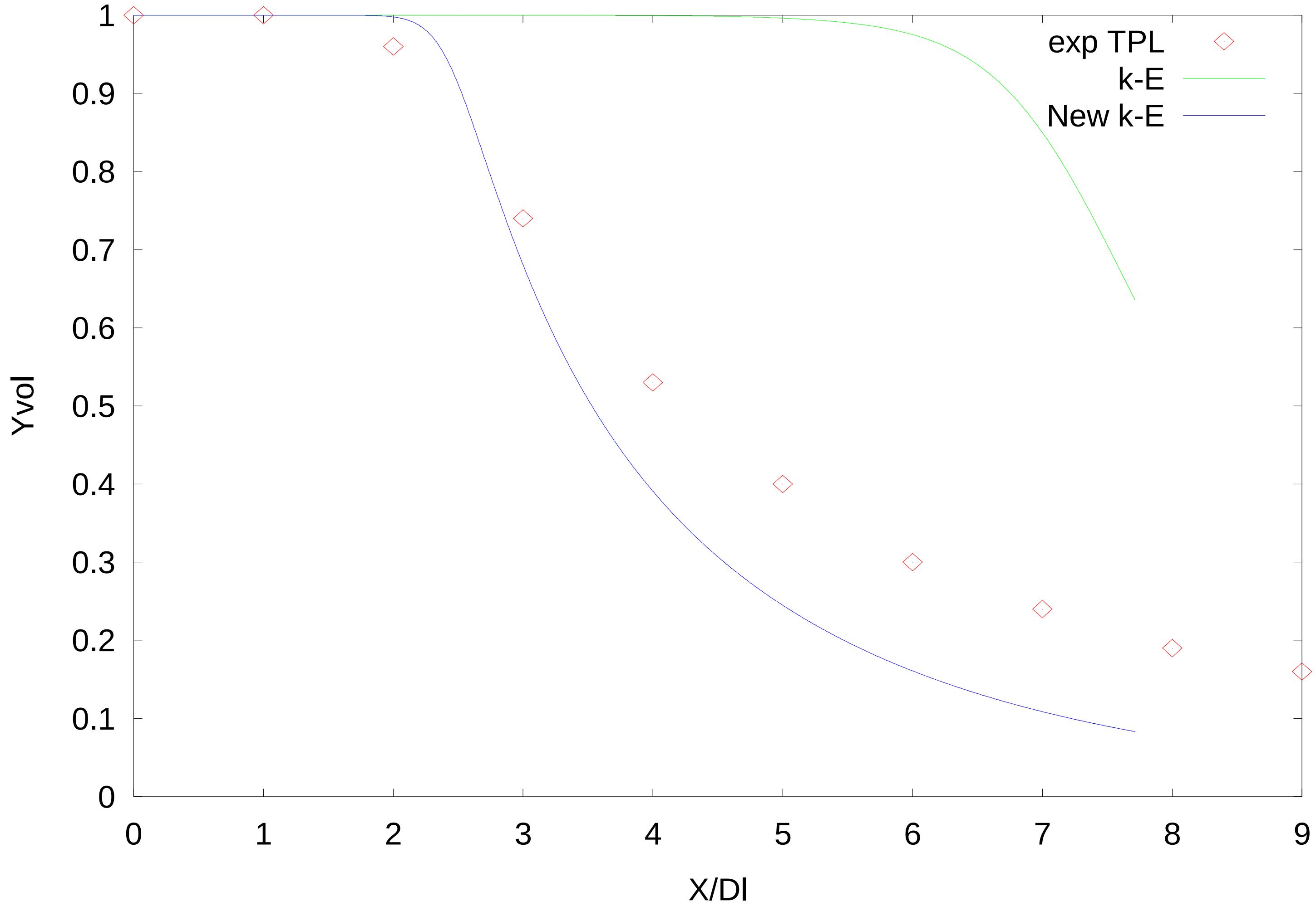
	Stepowski et al.	*Carreau et al.* TPL (liquid presence probability)		
Ugas	115	175	175	42
ρ_g	1.2	1.2	1.2	10.8
Uliquid	1.3	2.5	5	2.5
$J = \frac{\rho_g U_g^2}{\rho_l U_l^2}$	9.39	5.88	1.47	3.04

J=5.88



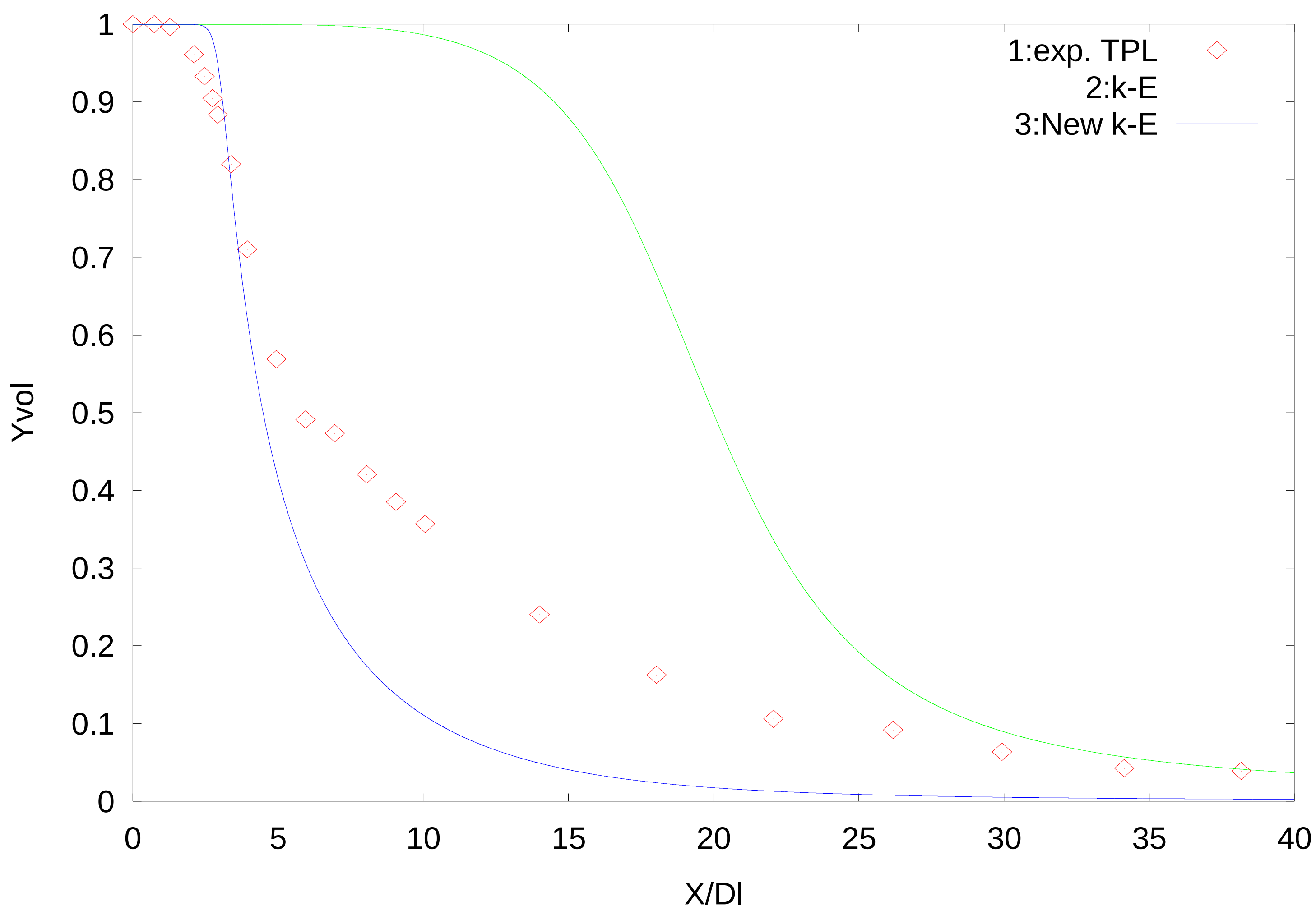
1:exp. TPL
2:k-E
3:New k-E
Yvol
X/Dl
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30
35
40

J=3.04



exp TPL
k-E
New k-E
Yvol
X/Dl
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9

J=1.47

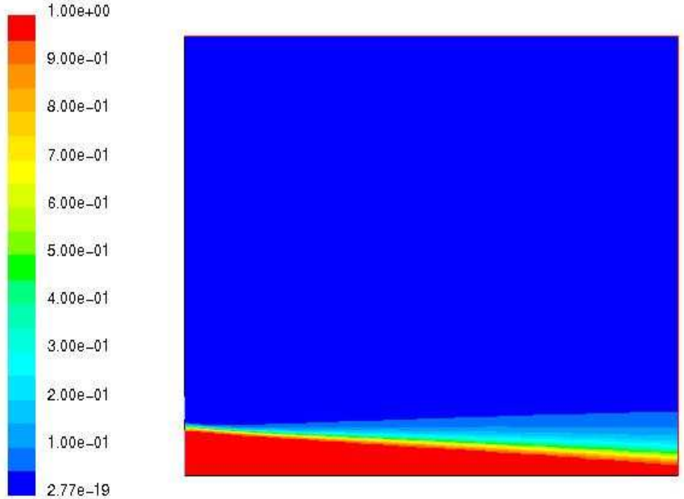


1:exp. TPL
2:k-E
3:New k-E
Yvol
X/Dl
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
40

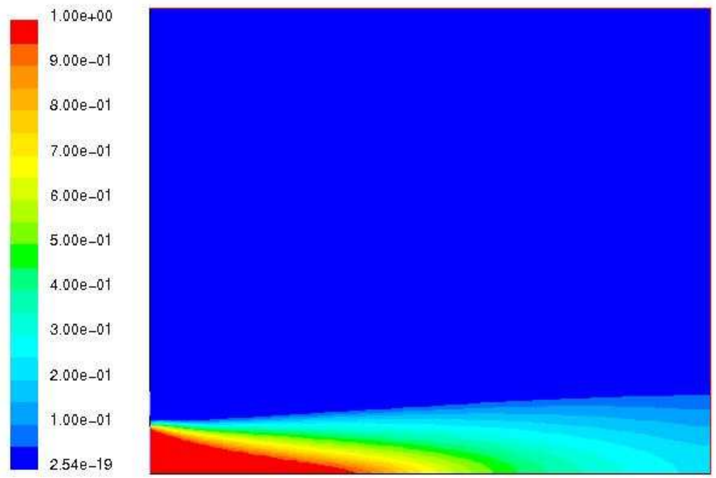
3D CFD Code (FLUENT)

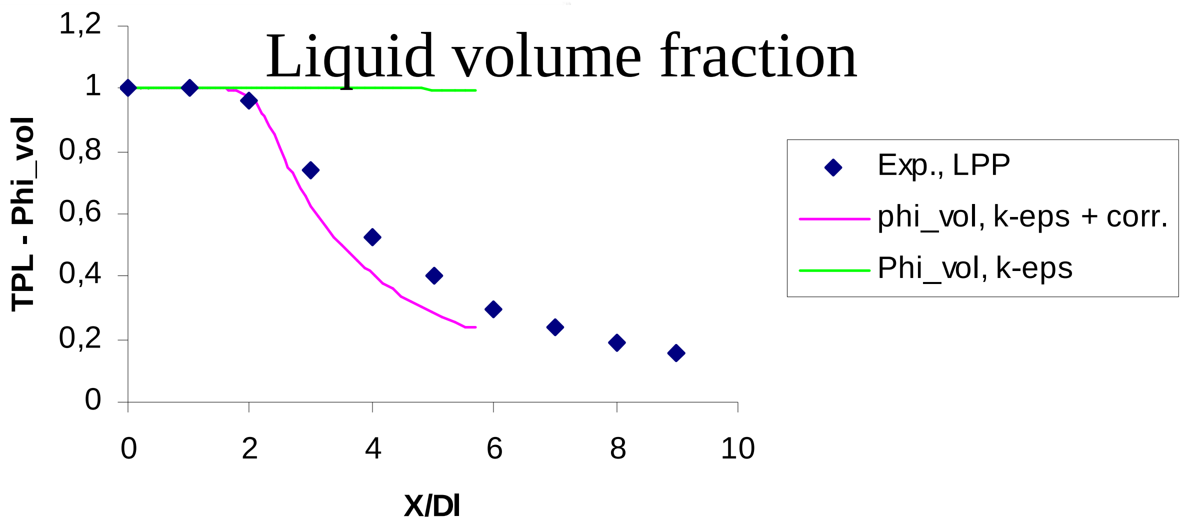
J=3.04

Standard model:



New model:





Application of ELSA model to Diesel atomization

Direct numerical simulation …

T. Ménard , S. Tanguy, A. Berlemont

Push at its limit

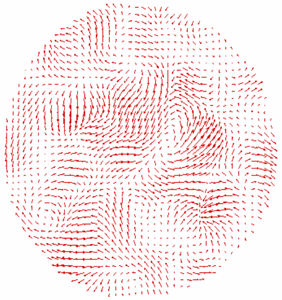
Physical case

Characteristics of the spray :

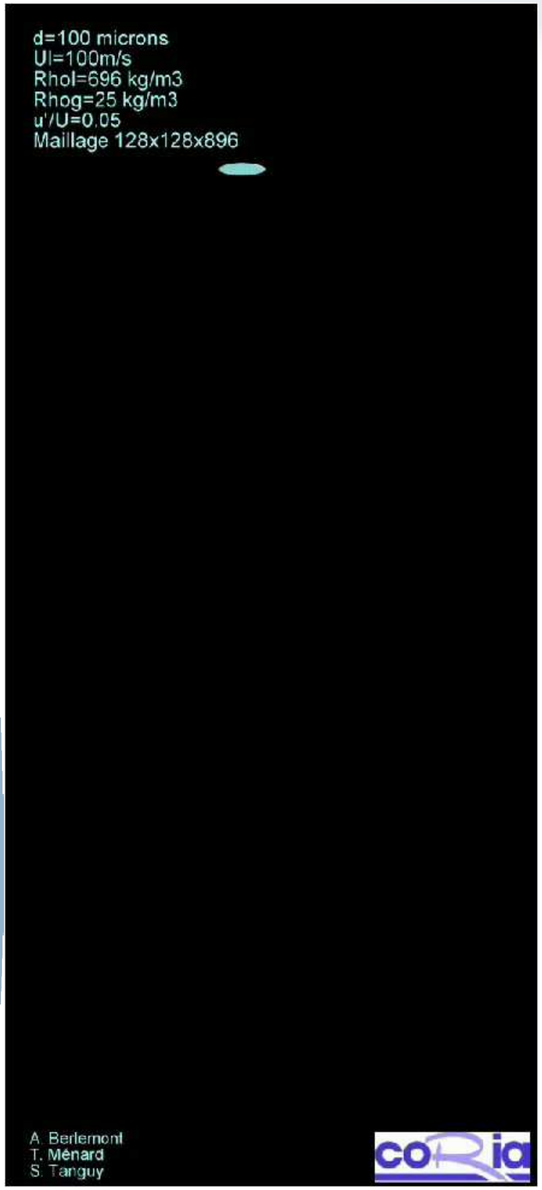
Diameter (D)	velocity	Turbulent intensity	Lenght scale
100 μm	100 $m.s^{-1}$	u'/U=0.05	0.1D
phase	Density	Viscosity	Surface tension
Liquid	696 $kg.m^{-3}$	$1.2\ 10^{-3}\ kg.m^{-1}.s^{-1}$	0.06 $N.m^{-1}$
gas	25 $kg.m^{-3}$	$1.\ 10^{-5}\ kg.m^{-1}.s^{-1}$	

Instantaneous Turbulent inflow :

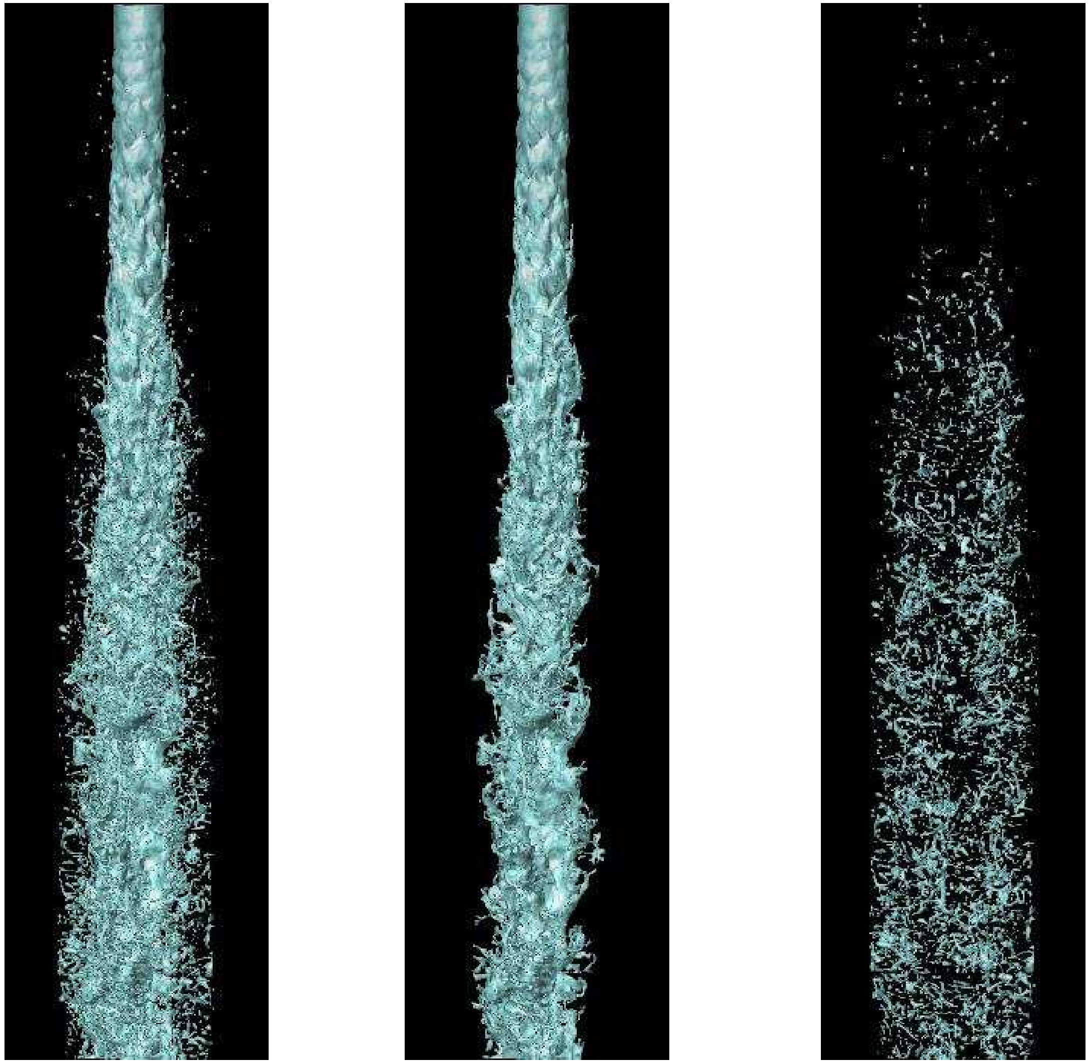
(Klein 2003)



Simulation of primary breakup (Diesel conditions)



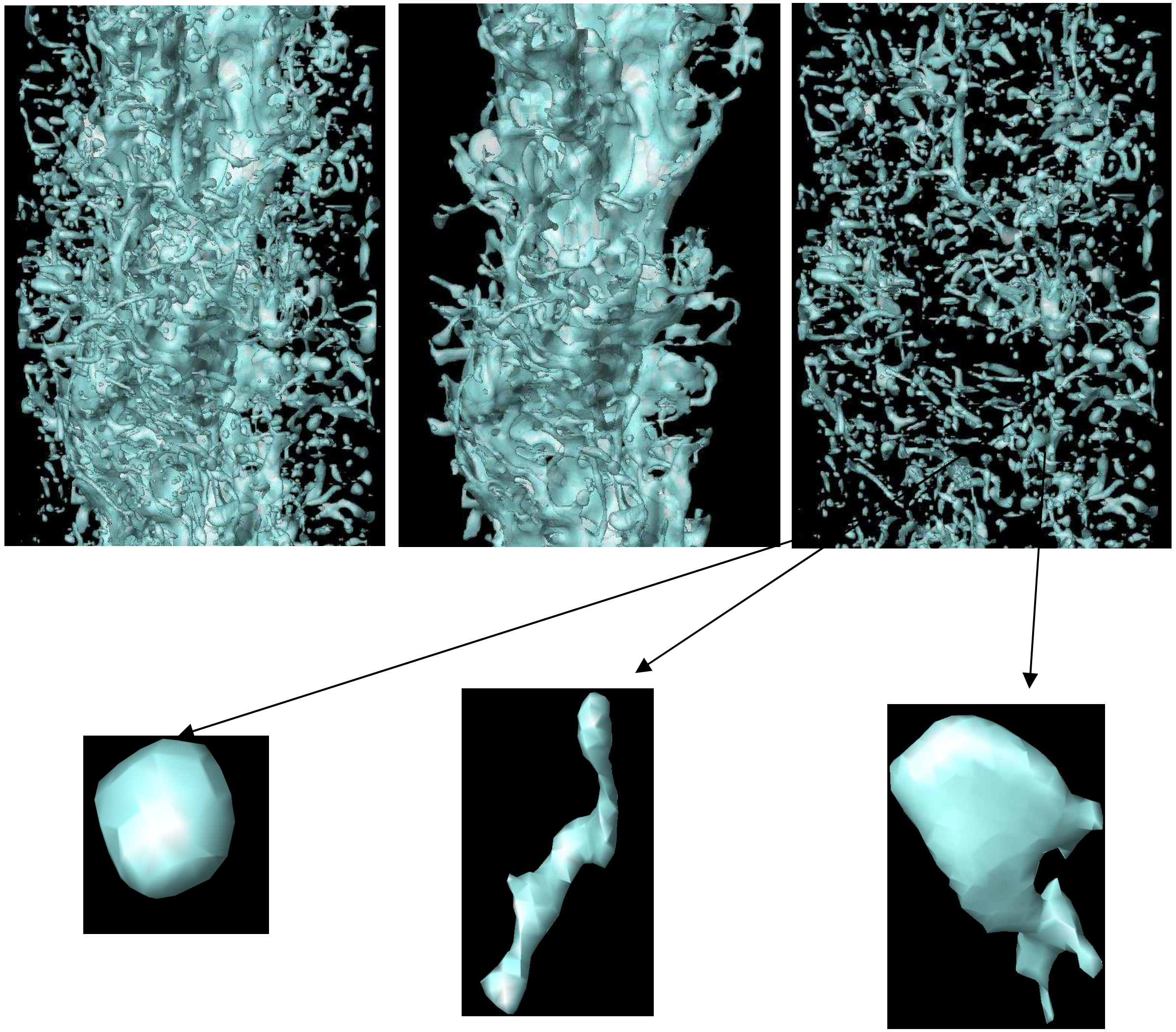
Complete | Attached | Detached



Coupling level set/VOF/ghost fluid methods: Validation and application to 3D simulation of the primary break-up of a liquid jet

T. Menard, S. Tanguy, A. Berlemont, IJMF 2007

Morphology



Model Comparisons

P.A. Beau, R. Lebas

Liquid volume fraction comparison

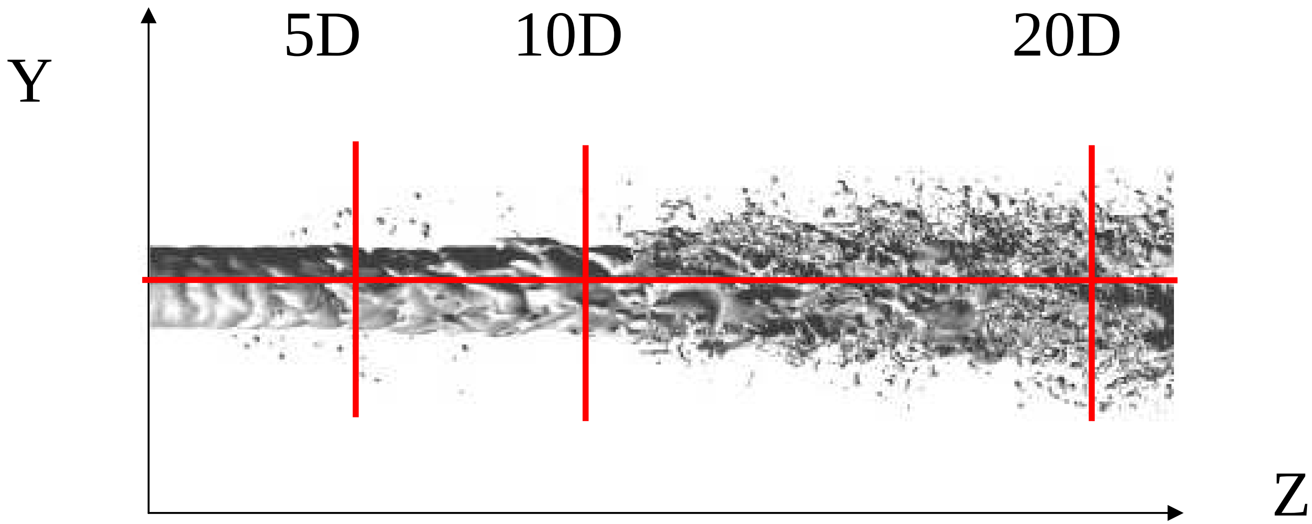
Transport of the liquid species:

$$\frac{\partial \bar{\rho}\tilde{Y}_l}{\partial t} + \frac{\partial \bar{\rho}\tilde{U}_j\tilde{Y}_l}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\bar{\rho}D_t\frac{\partial \tilde{Y}_l}{\partial x_j}\right)$$

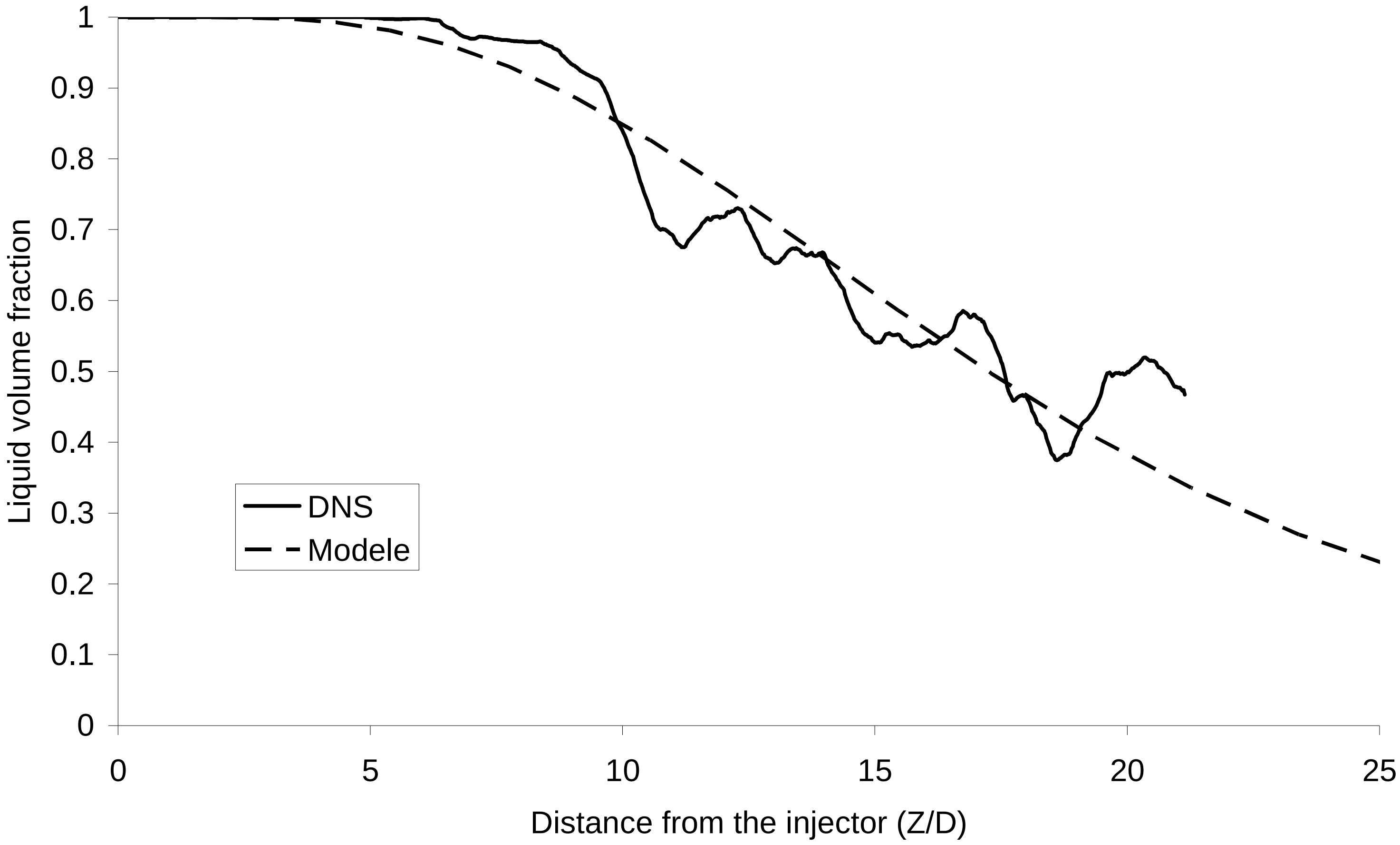
Classical turbulent diffusion + k-ε

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

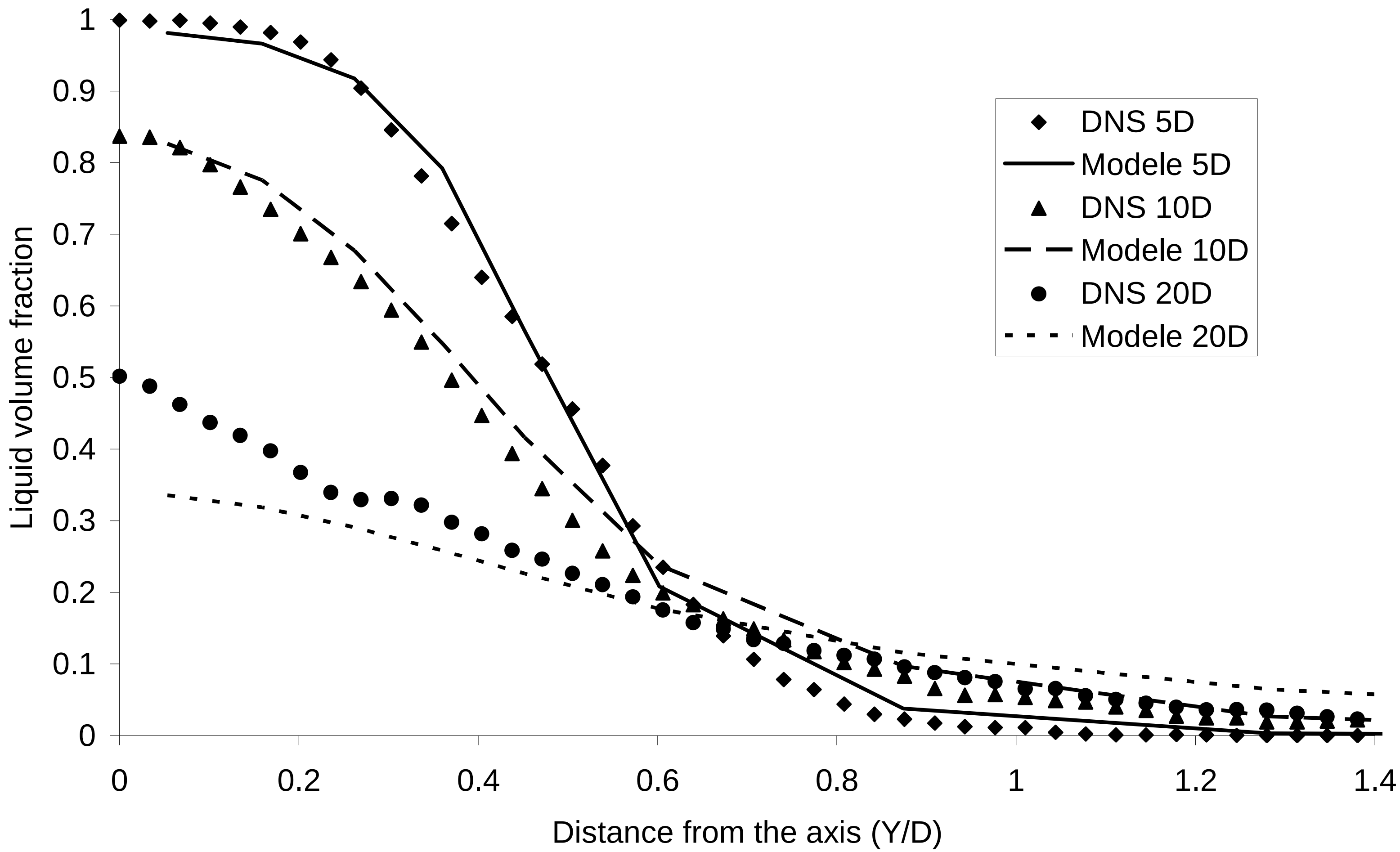
ε



Axial profile



Radial profiles



Surface density comparison

$$\frac{\partial\overline{\Sigma}}{\partial t}+\frac{\partial\tilde{u}_j\overline{\Sigma}}{\partial x_j}=\frac{\partial}{\partial x_j}\left(D_t\frac{\partial\overline{\Sigma}}{\partial x_j}\right)+(|A|+a_{coll}).\overline{\Sigma}-V_s.\overline{\Sigma}^2$$

- Production due to the mean flow stretching

$$A=\alpha_0\frac{\overline{\rho u''_i u''_j}}{\overline{\rho}k}\frac{\partial\tilde{u}_i}{\partial x_j}$$

- Production due to collision effects

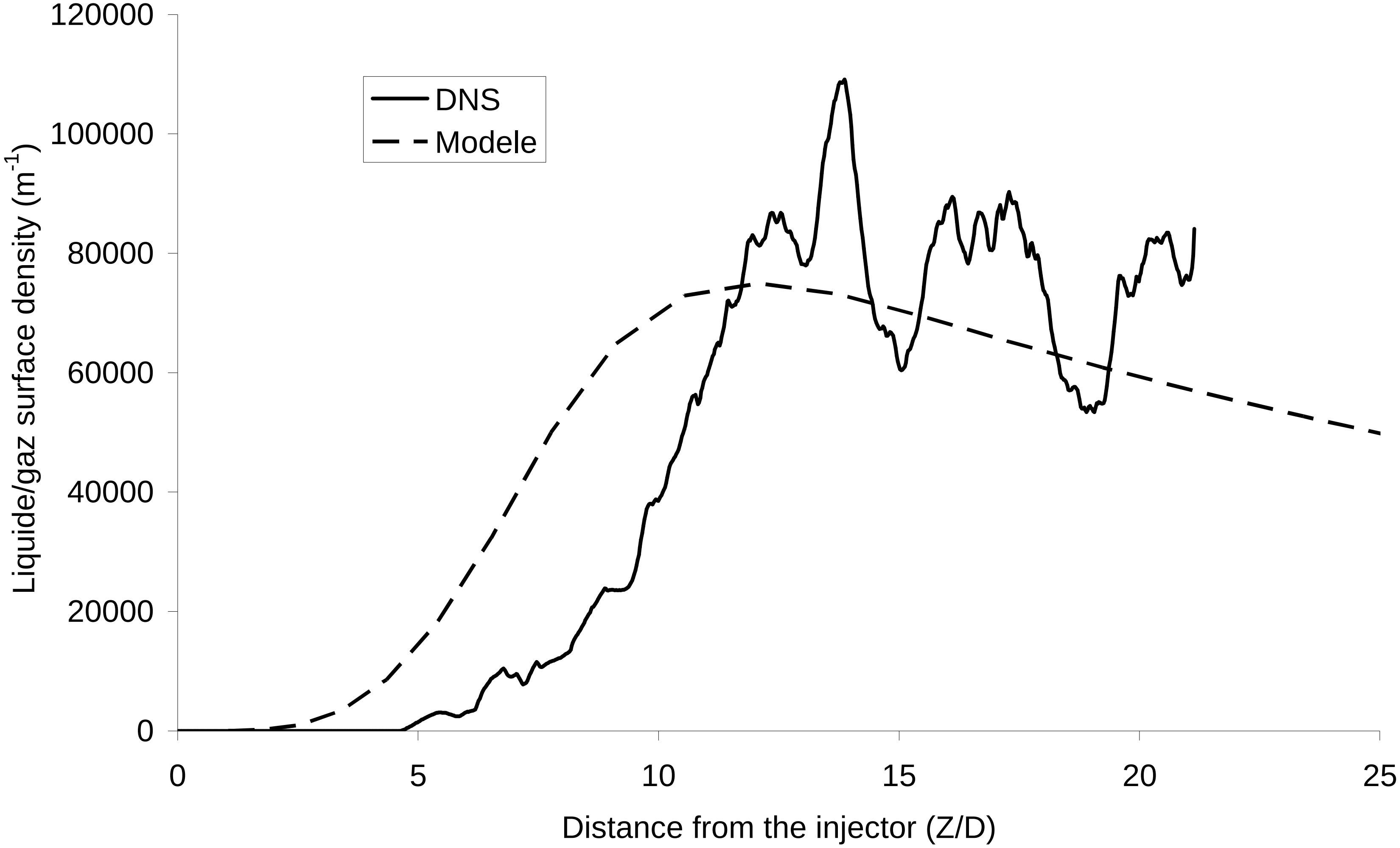
$$a_{coll}=\frac{\alpha_1}{(36\pi)^{2/9}}\left(l_t\overline{\Sigma}\right)^{2/3}\left(\frac{\rho_l}{\overline{\rho}\tilde{Y}_l}\right)^{4/9}\frac{\varepsilon}{k}$$

- Equilibrium, surface tension effect

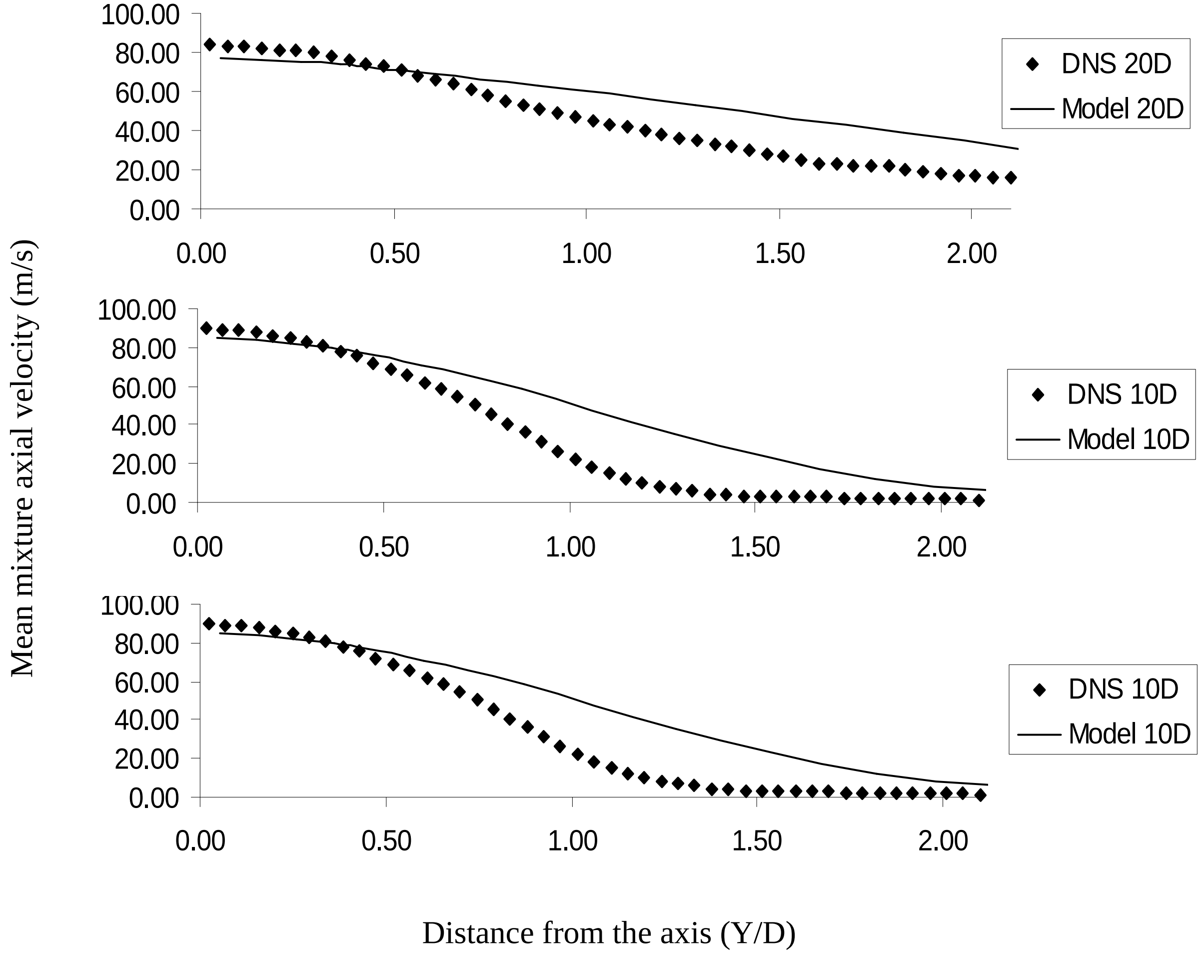
$$V_s=\frac{a_{coll}\rho_l r_{eq}}{3\overline{\rho}\tilde{Y}_l} \qquad r_{eq}=C\frac{\sigma^{3/5}l_t^{2/5}}{k}\frac{\left(\overline{\rho}\tilde{Y}_l\right)^{2/15}}{\rho_l^{11/15}}$$

A. Vallet, A. A. Burluka and R. Borghi, Atomization and Sprays, 2001

Axial profile



Radial profiles



Conclusions and perspectives

➔Global turbulent approach (like k-ε) can be applied to describe first atomization for high Weber and Reynolds number

➔Such models are necessarily to couple atomization with injector flow

➔ Liquid dispersion in such cases can be described like turbulent mixing accurately

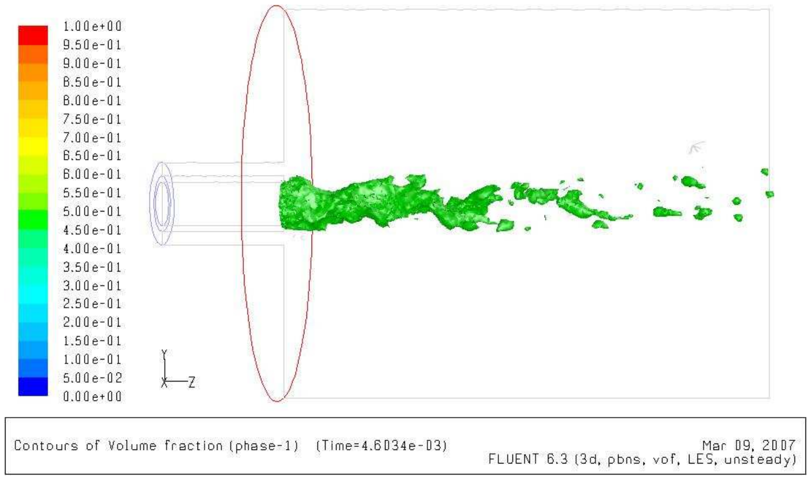
➔Main instability mechanisms should be incorporated in the model

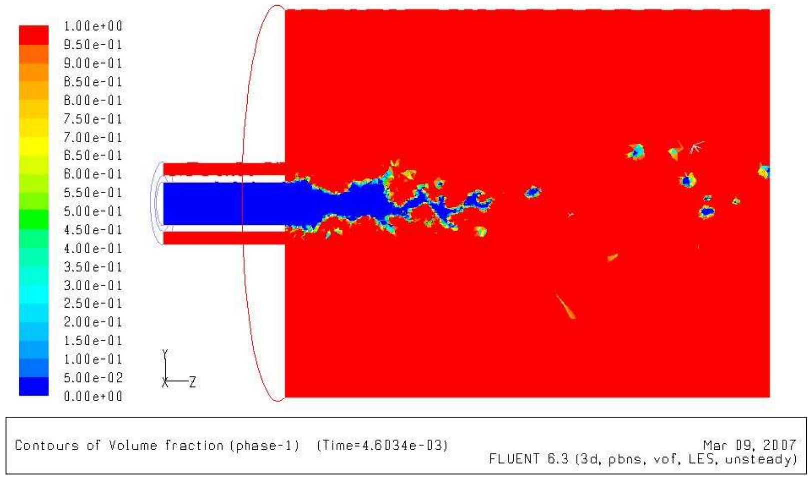
➔Still very complex phenomena are involved in addition to ‘regular’ turbulence

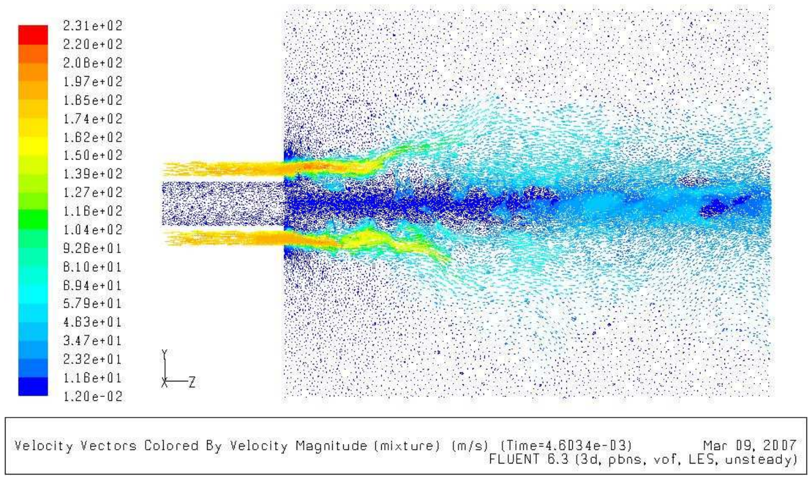
➔How things would be improved by using LES ?

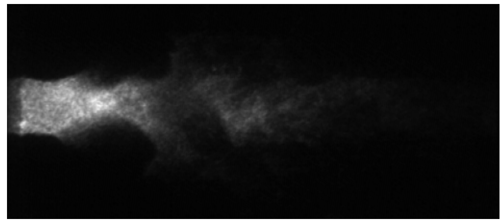
GOAL : LES of atomisation

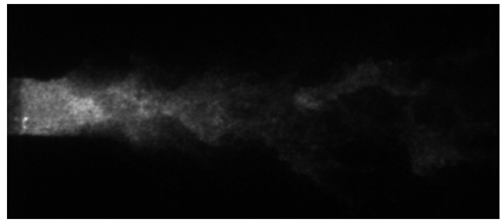
Test coaxial injector:







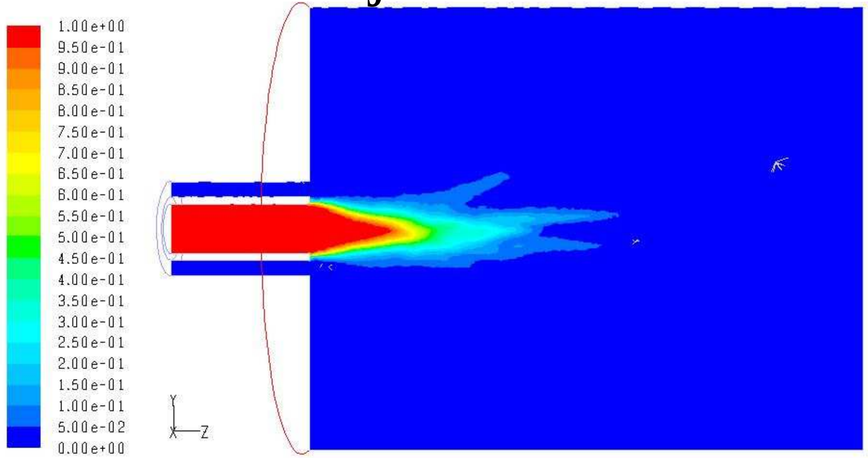


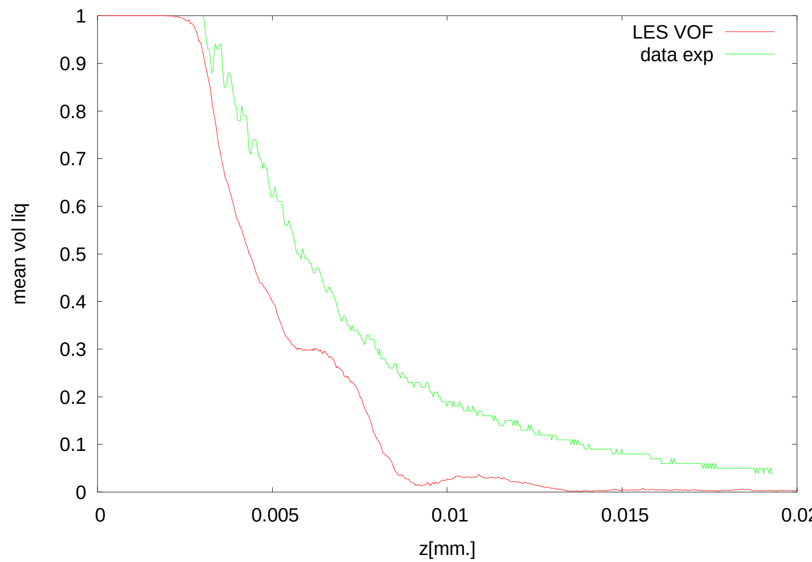


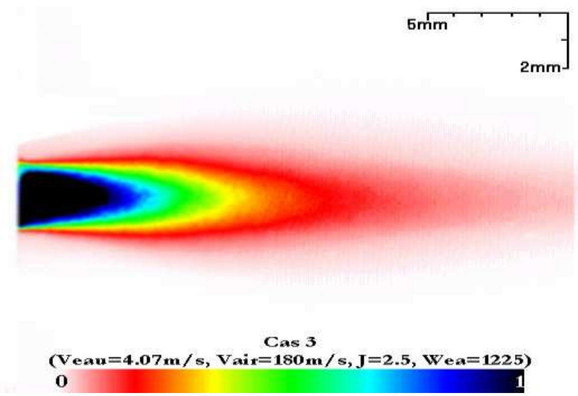
GOAL : LES for velocities and liquid/interface TO the SPRAY

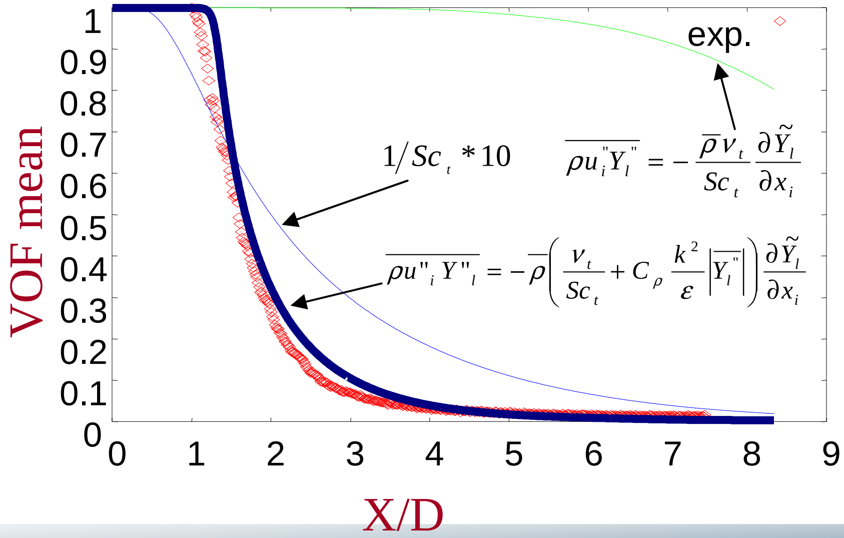
Mean

Test coaxial injector:







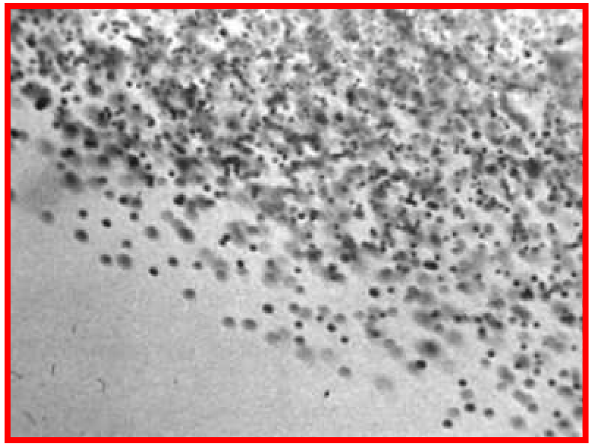


Out line

Part I : Introduction to atomization and two-phase flow modeling

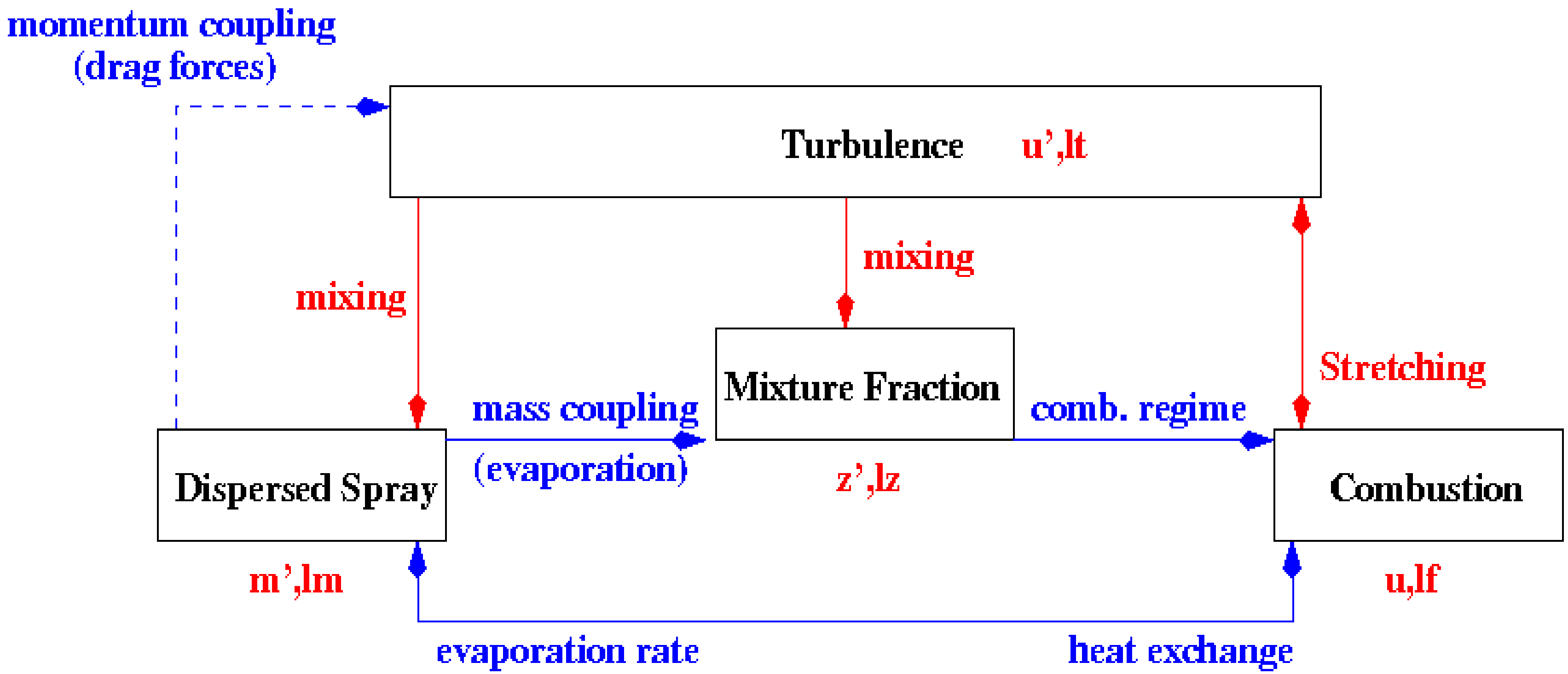
Part II : Turbulence mixing approach for atomization

Once the droplet are formed …



Part III : Turbulence, droplet, vaporization, mixing and combustion

Spray/Turbulence/Combustion interactions



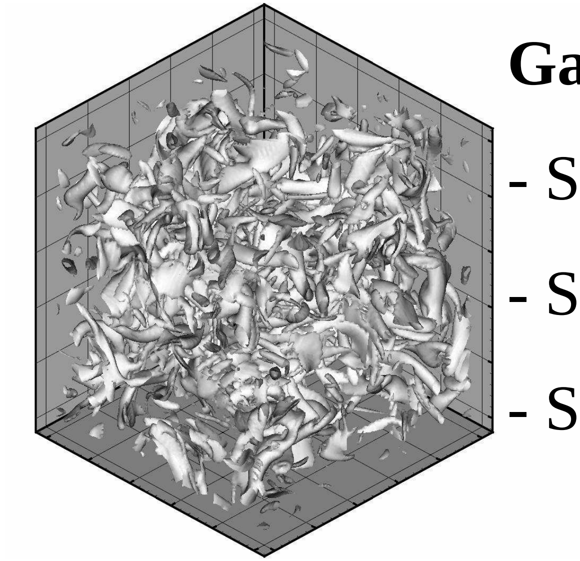
Droplet dynamics induced preferential segregation (➔see course of J. Bec):

➔ impact on droplet evaporation rate ?

➔ impact on mixture fraction topology ?

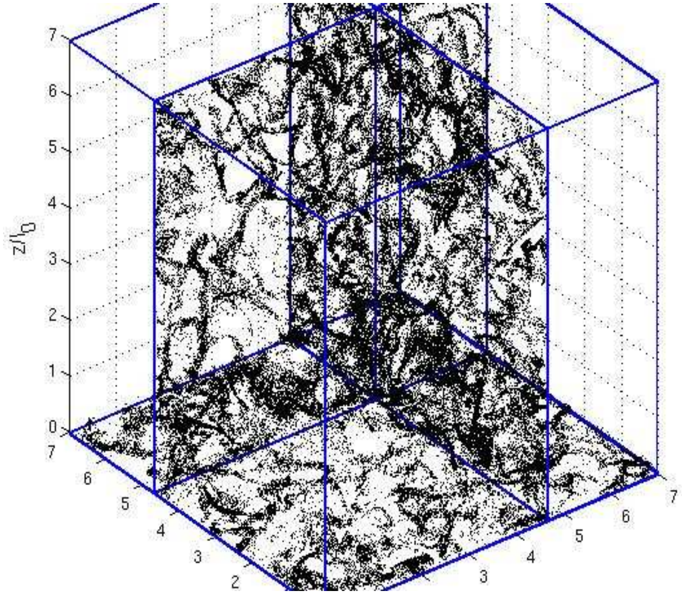
➔ impact on flame structure and propagation ?

Configuration: isotropic turbulence



Gas Phase: DNS

- Spectral resolution
- Semi-deterministic forcing scheme
- Statistically stationary properties (u', l_t, ε)



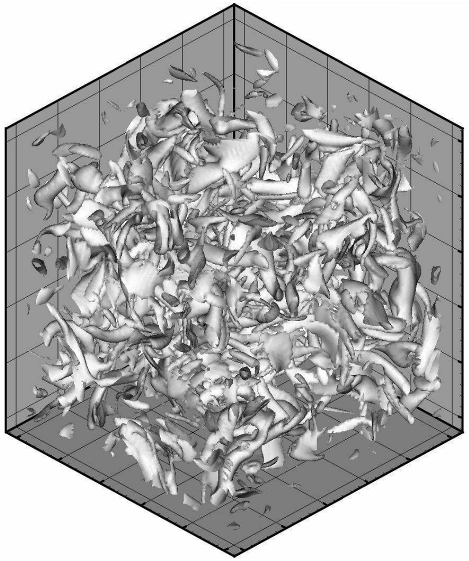
Dispersed Phase: Lagrangian solver

- 1-way momentum, 2-way vapor
- Monodispersed spray
- Control parameter:

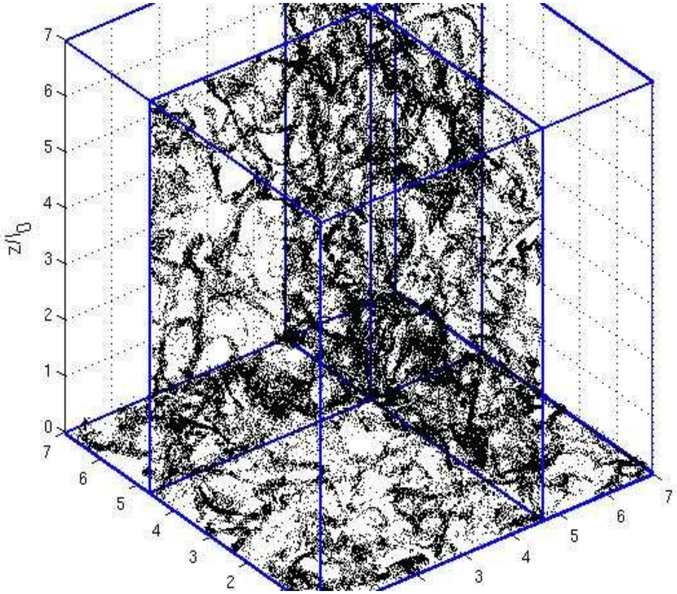
Stokes number: $St = \dfrac{\tau_p}{\tau_\eta}$

129^3 nodes and > 10^6 droplets

A 4 step numerical procedure

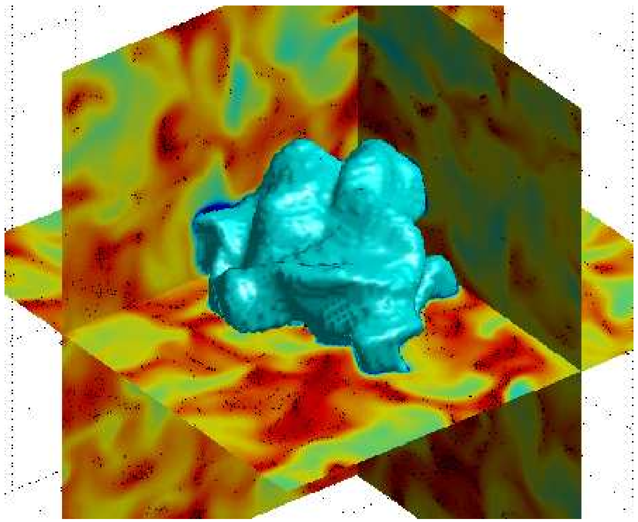


1. Statistically stationary turbulence



2. Spray dynamical equilibrium

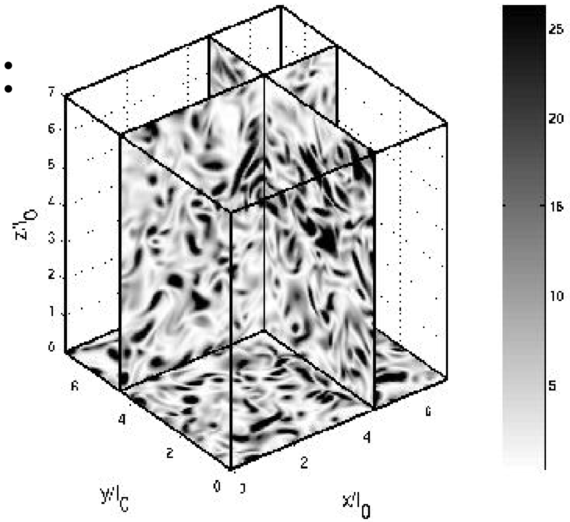
3. Liquid phase evaporation



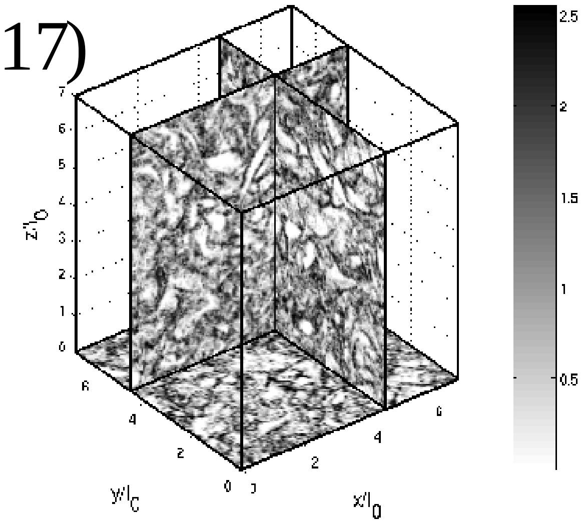
4. Flame ignition and propagation

Liquid density: ξ , mean value: $\bar{\xi} = 1$

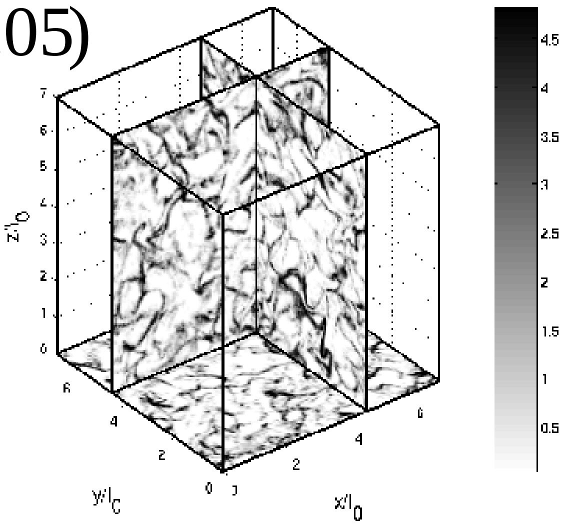
Vorticity:



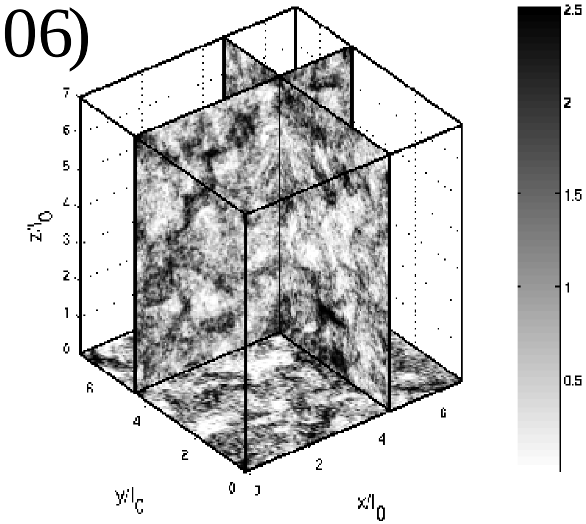
$\xi(St = 0.17)$



$\xi(St = 1.05)$

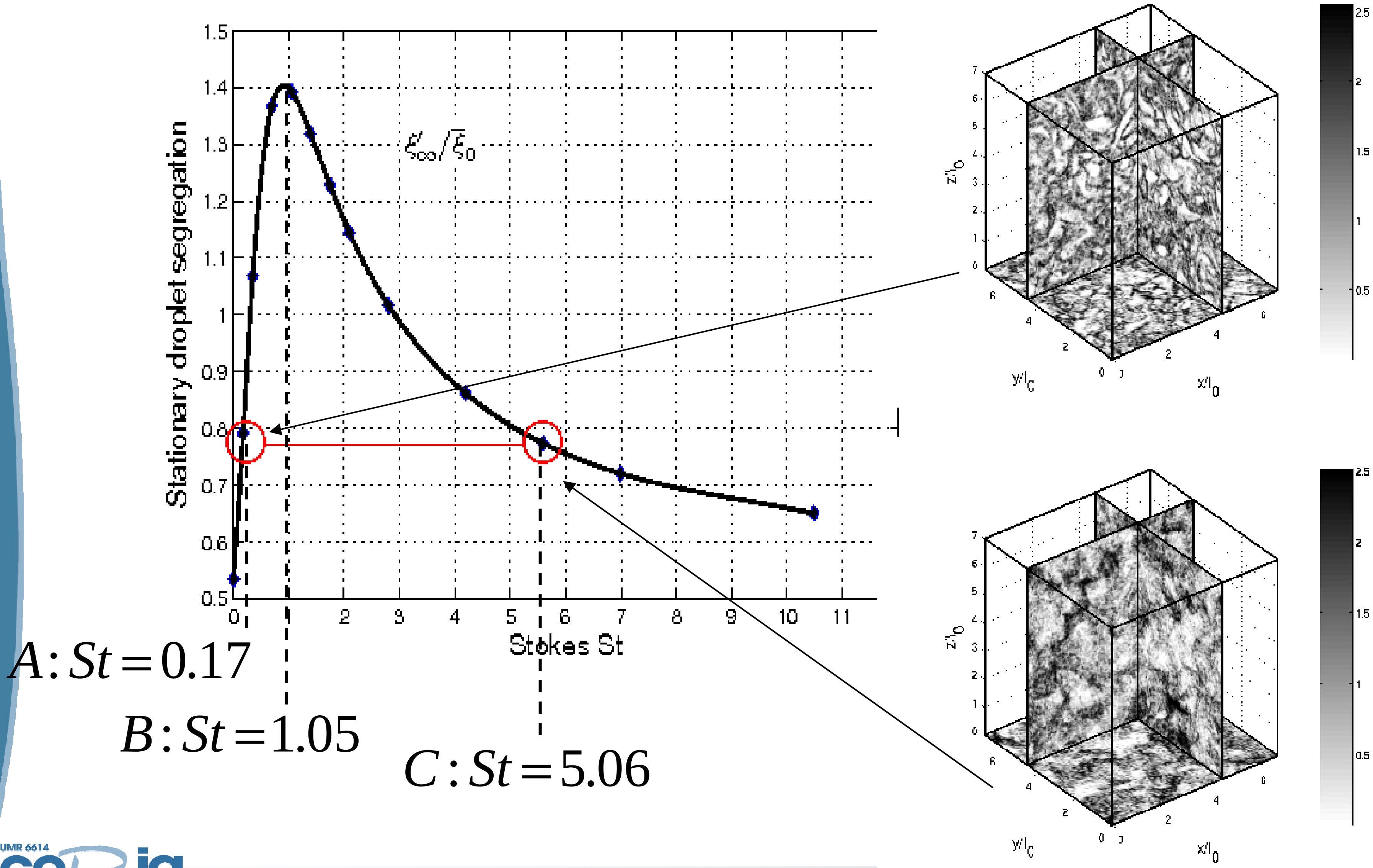


$\xi(St = 5.06)$



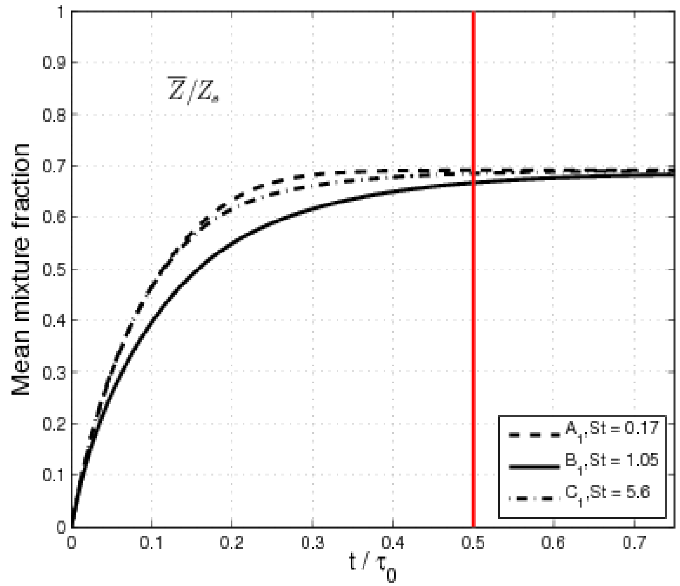
Segregation efficiency:

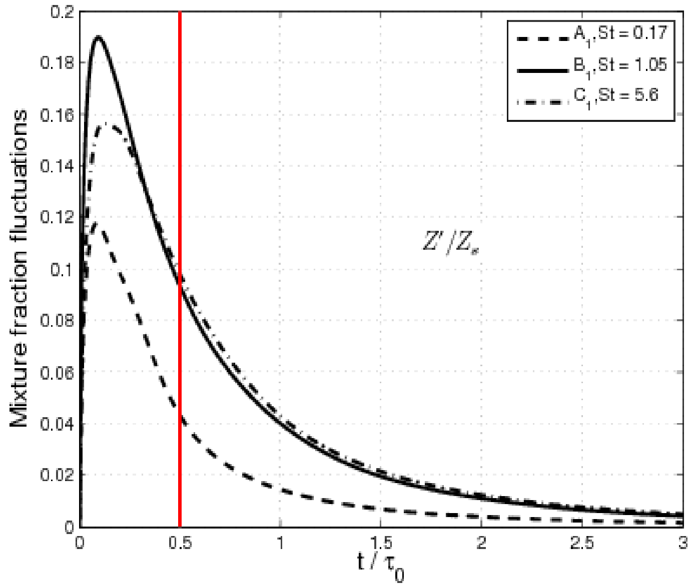
Droplet ejection ⇔Turbulent mixing⇔Ballistic trajectories



Impact on Evaporation

Z= vapour mass fraction

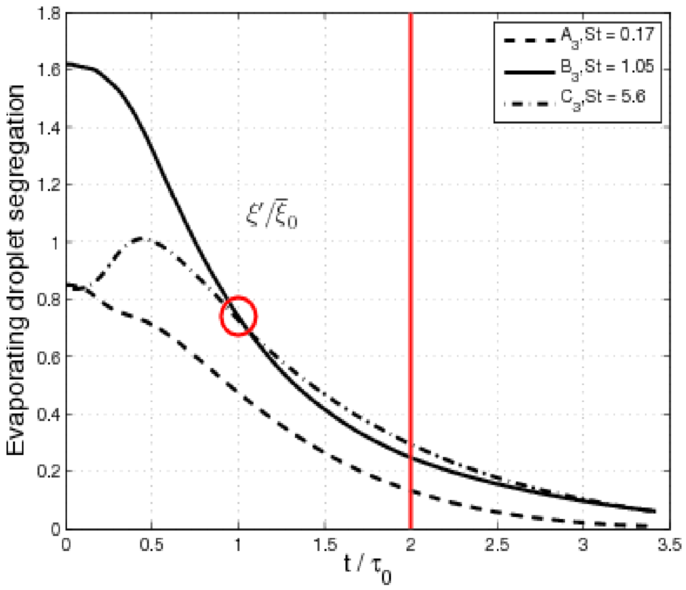


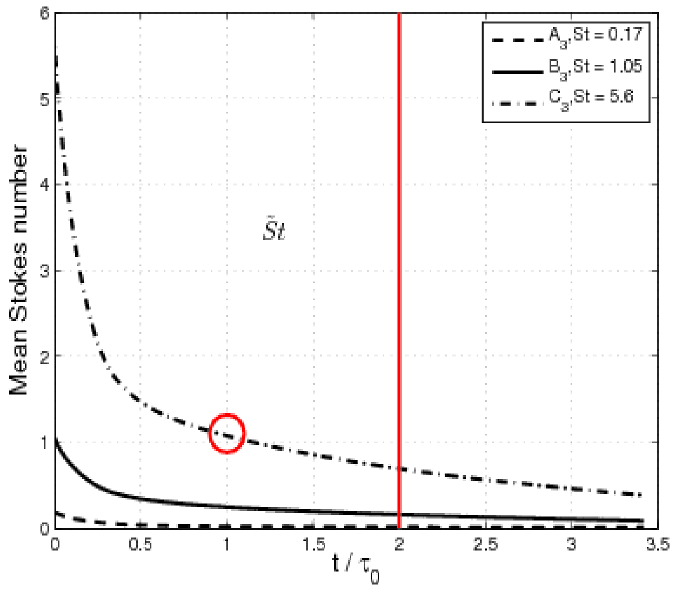


- A and C evaporates faster than B: $if\ \xi'\downarrow then\, W_v \uparrow$
- Case A (light) evaporates faster than C: $\xi_A' = \xi_C'\ but\ W_{vA} \neq W_{vC}$
- Case C (heavy) evolves from A to B: C⬄A➔C⬄B

Segregation➔up to 100% variation on *Z'*

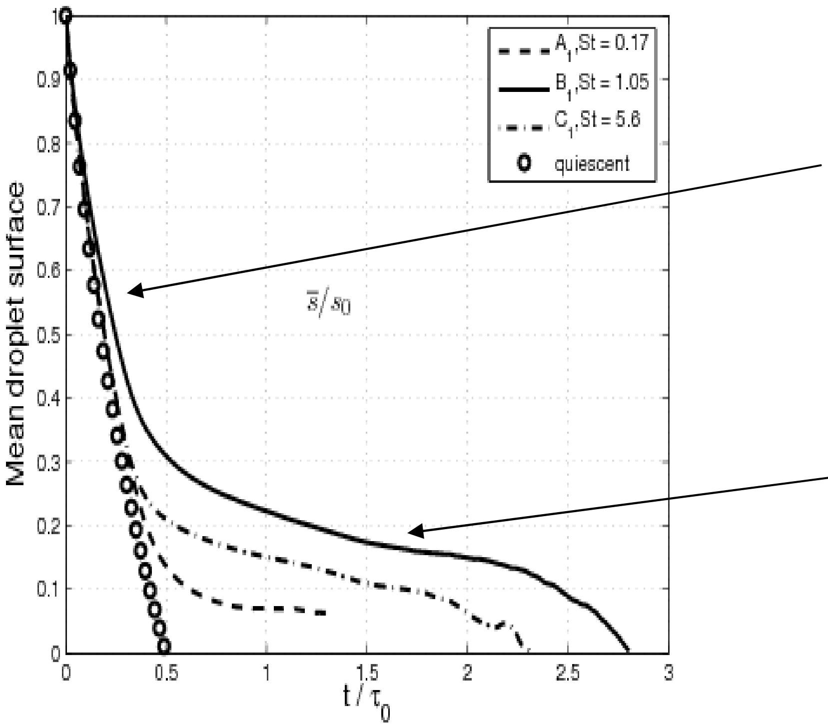
Liquid segregation and Stokes number evolution





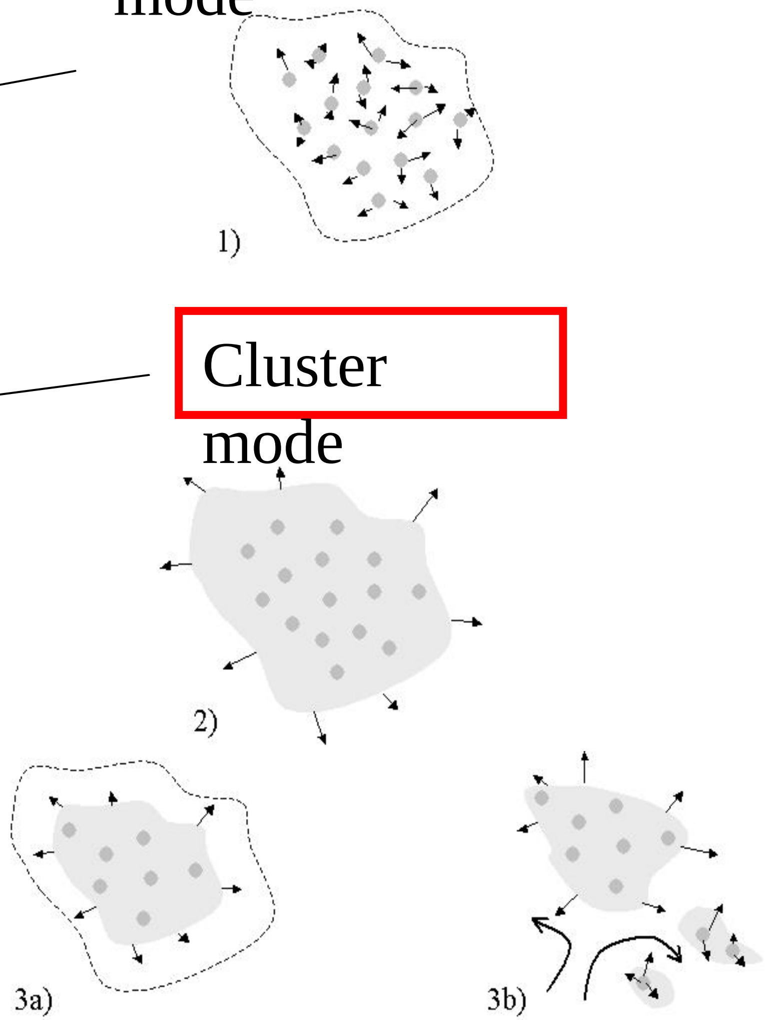
- Evaporation ➔ evolution of Stokes number
- Case C : first segregation increases
- Case C merges with case B when $St = 1$

Evaporation regimes

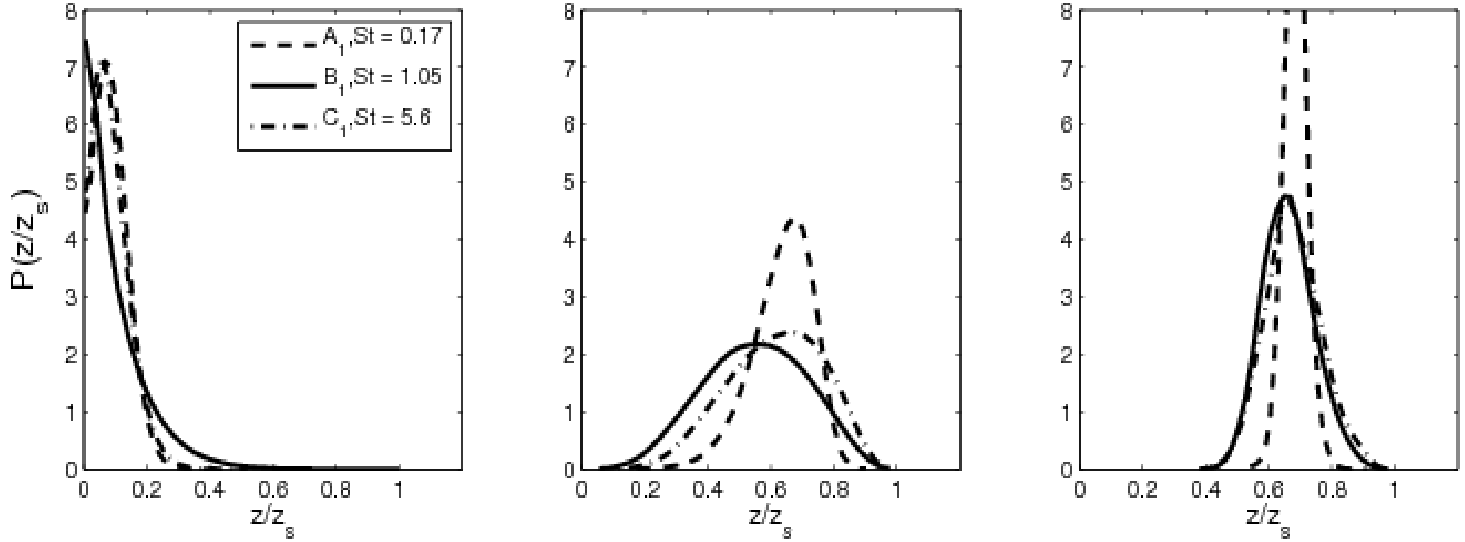


Single droplet mode

Cluster mode



PDF shape and evolution



Early stage:

$$P_A(Z) = P_C(Z)$$

B: Less mixed

Intermediate stage:

Cluster effect

$$P_A(Z) \neq P_B(Z) \neq P_C(Z)$$

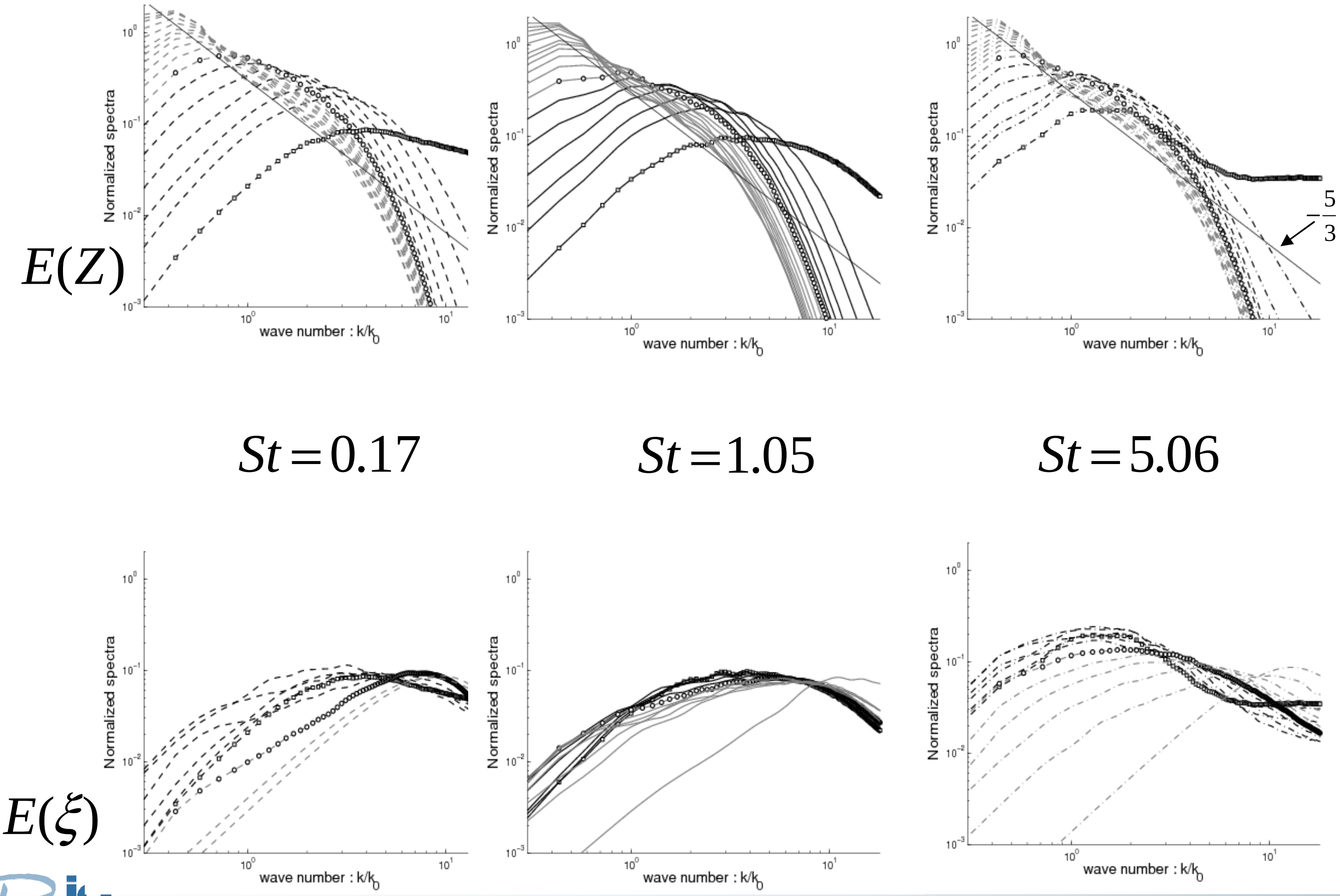
Final stage:

$$P_B(Z) = P_C(Z)$$

A: More mixed

Gaussian PDF

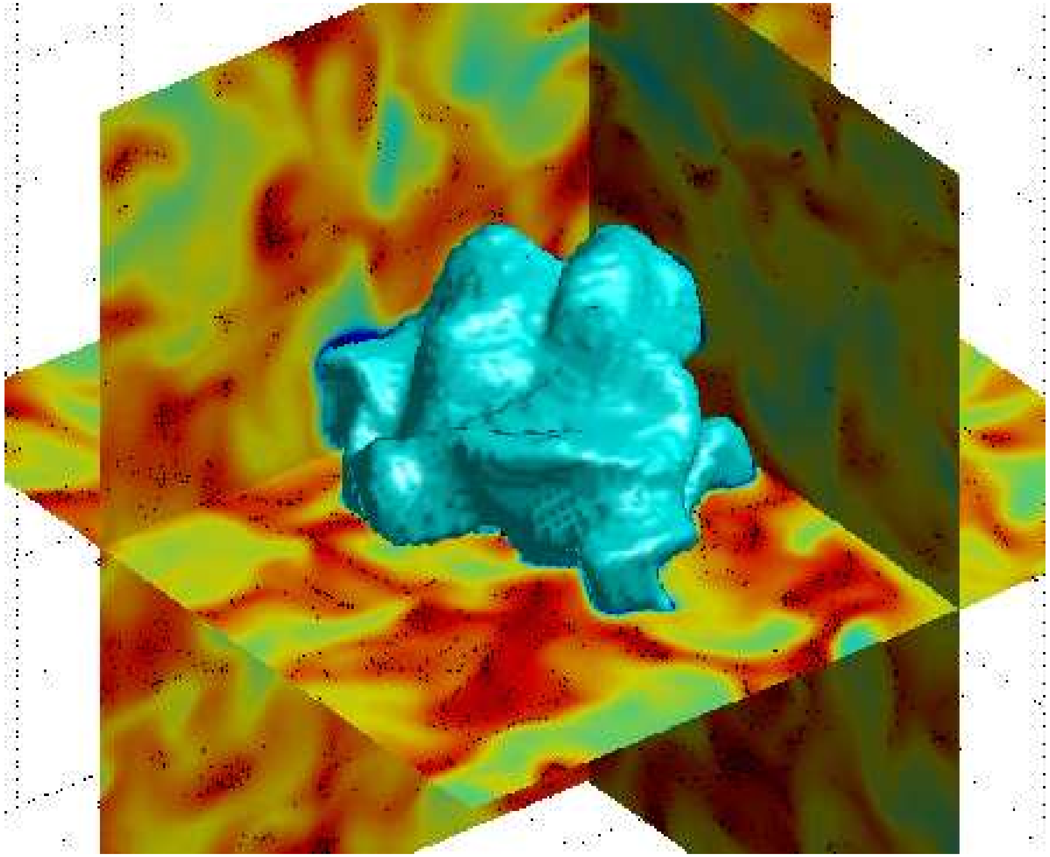
Energy Spectra of Z and ξ



Summary for segregation on evaporation:

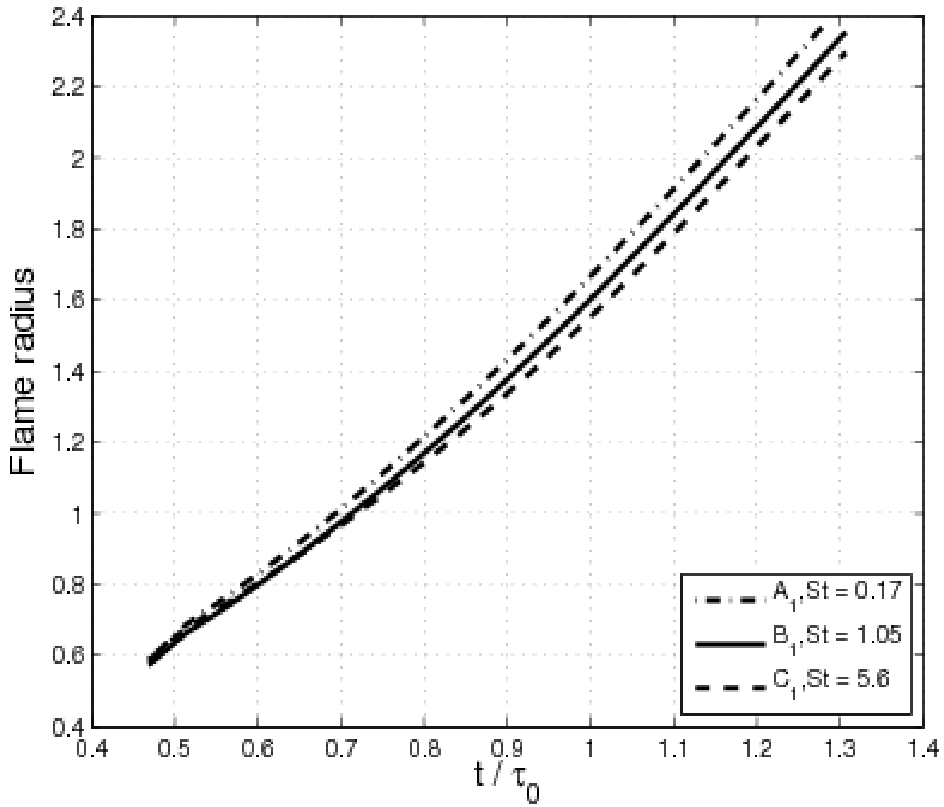
	$\bar{Z}$	Z'	$P(Z)$	E_Z	E_ξ
$t \approx 0$	$-$	$-$	$-$	$+$	$+$
$0 < t < \tau_v$	$+$	$++$	$++$	$+/-$	$+$
$t > \tau_v$	$-$	$++$	$-$	$-$	$+$

Globally premixed flame propagation:



Case B

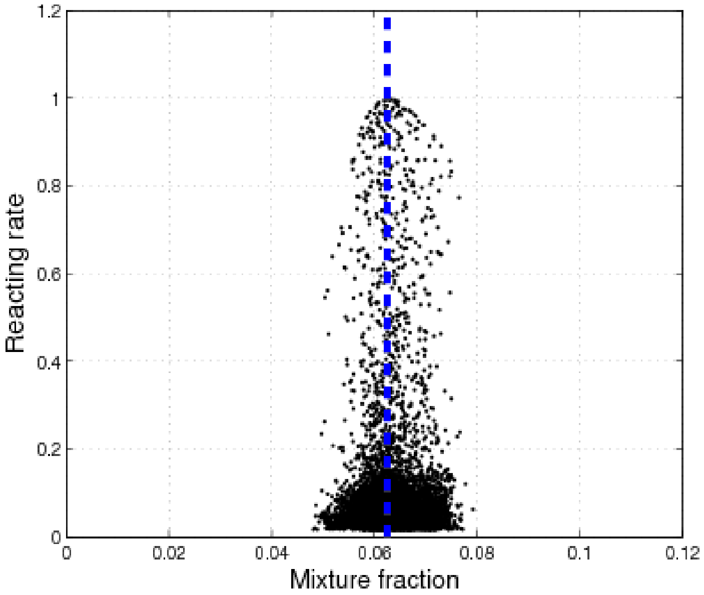
Mean Flame Radius vs Time:



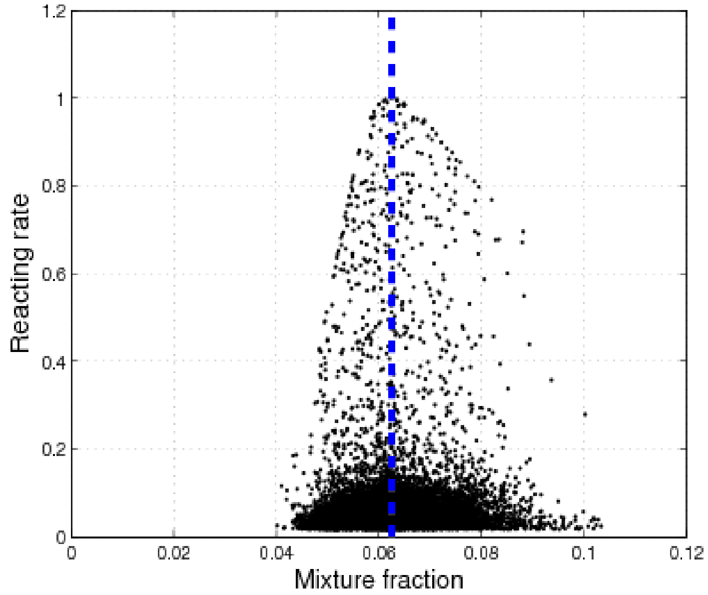
Late ignition: $\tau_{ign} = \tau_v$ and $u_l < u'$

➔weak influence of segregation on flame propagation

Scatter plot: reaction rate vs mixture fraction



$St = 0.17$



$St = 1.05$

Same mean behaviour but different local flame structures

Conclusion for segregation effect on evaporation

- Liquid density ξ characterises the spray segregation
- Parallel comparisons of liquid and vapour fields
- First two moment of ξ insufficient to characterise segregation

  ➔ Topological information needed

- The segregation plays a major role on vapour fluctuations
- For $\tau_{ign} = \tau_v$ and $u_l < u'$ turbulence flame speed not really affected
- Still, local flame structure is influenced

Conclusions & Perspectives

- Certain aspects of two-phase flow involved turbulence
- Additional phenomena have to be taken into account:

  Inertia, surface tension, phase change …

➔Still many open questions

- But in some cases, classical turbulence approaches give interesting results

… thank you for your attention.