Combustion diphasique
Atomisation et sprays

Julien Jouanguy

Luis Le Moyne

Les sprays et leurs applications

Médical

Incendies

Agriculture

Spatial

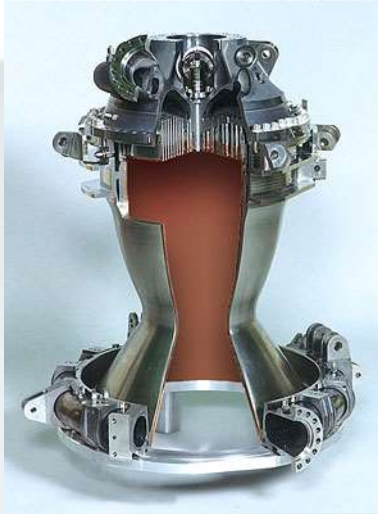
Les sprays et leurs applications

Combustion

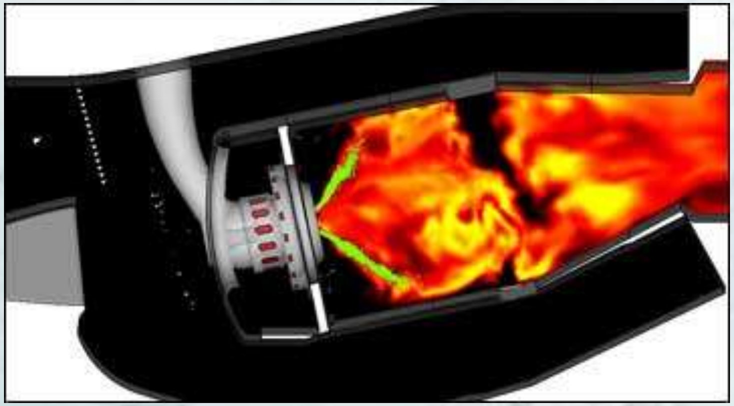
Refroidissement

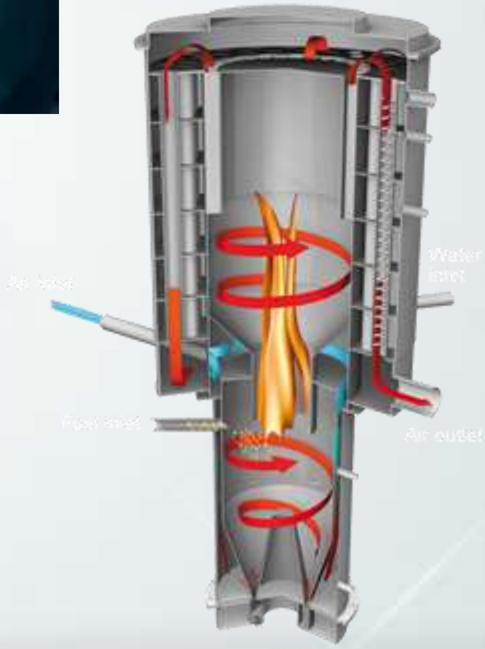
Traitement de surface

Les sprays et la combustion



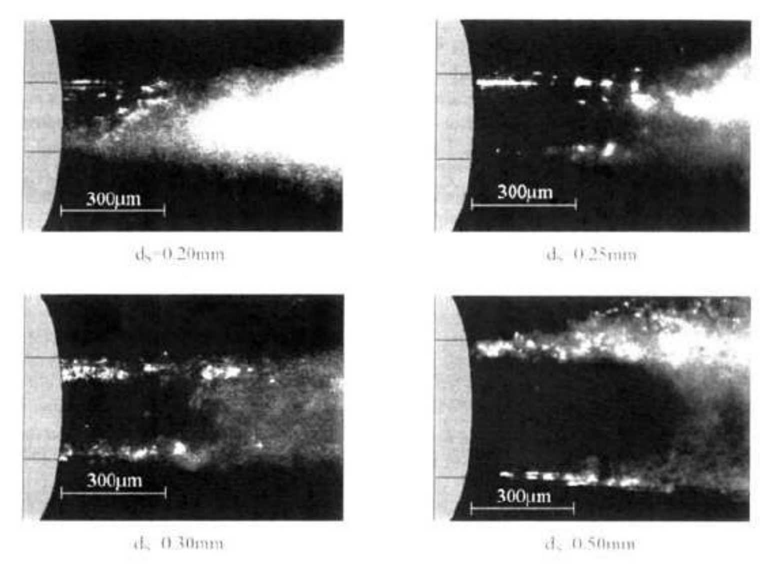
- Automobile
- Aéronautique
- Spatial
- Energie





Les sprays et la combustion

Des écoulements complexes….



Visualisation des structures internes d’un jet diesel

A. Fath*, K. Münch and A. Leipertz* “Spray Break-up Process of Diesel Fuel Investigated Close to the Nozzle”, ICLASS’97, Séoul, Corée, p. 513-520, 1997.

Jet d’oxygène et jet d’hydrogène à 1MPa

Gicquel,P. Vingert, L., Lecourt, R. & Barat, M. 2001, Etude expérimentale des sprays cryotechniques dans des conditions sub et supercritiques, GDR combustion dans les moteurs de fusée

Les sprays et la combustion

Pourquoi ?

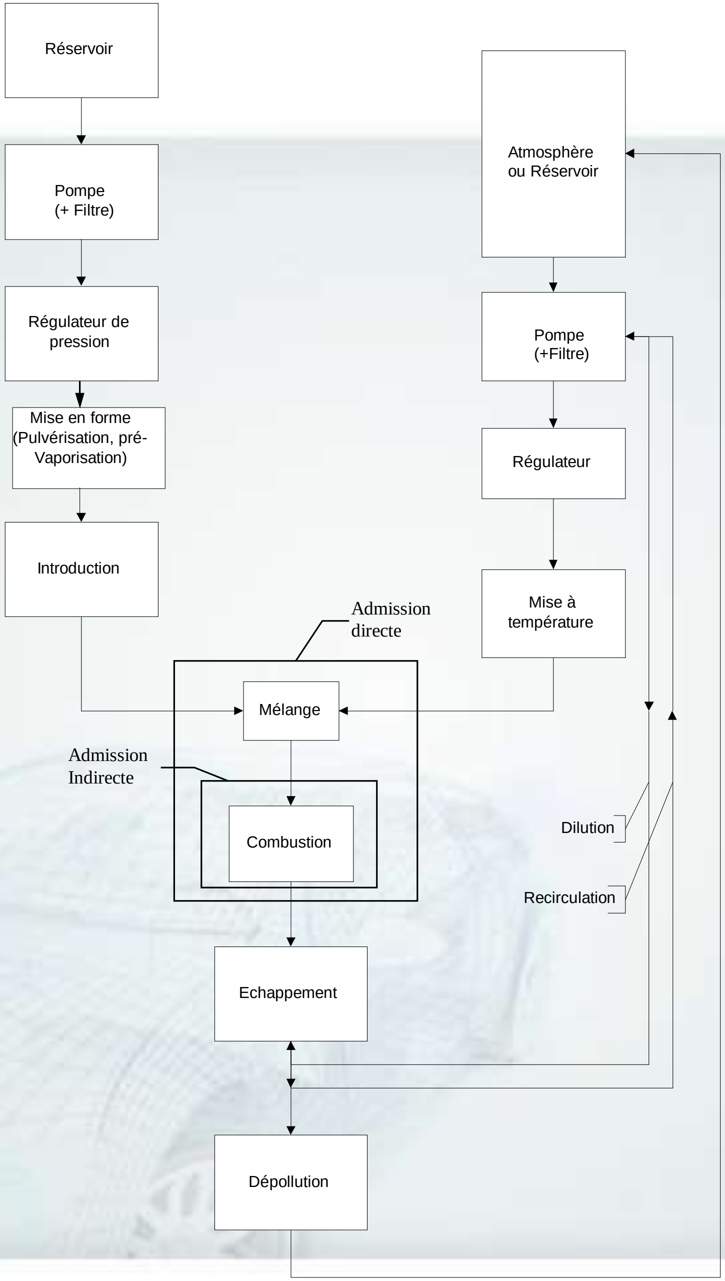
Stockage->combustible liquide

Comment ?

le passage à des gouttes diminue le temps d’évaporation et concentre la zone réactive

Pb. d’échelle : ~10ms, ~5cm, ~10mg

Préparation du mélange



Réservoir

Pompe
(+ Filtre)

Régulateur de
pression

Mise en forme
(Pulvérisation, pré-
Vaporisation)

Introduction

Atmosphère
ou Réservoir

Pompe
(+Filtre)

Régulateur

Mise à
température

Admission
directe

Mélange

Admission
Indirecte

Combustion

Dilution

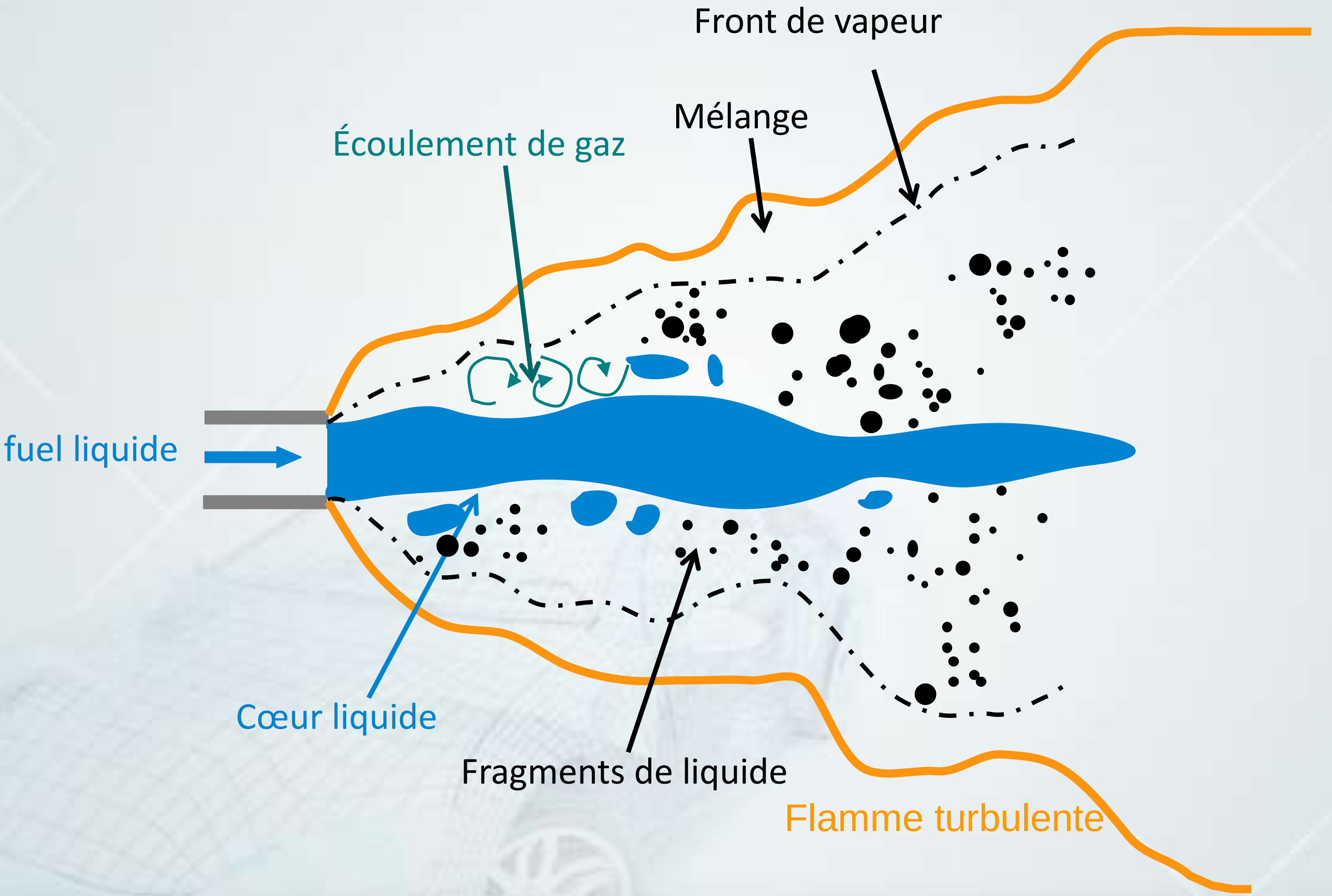
Recirculation

Echappement

Dépollution

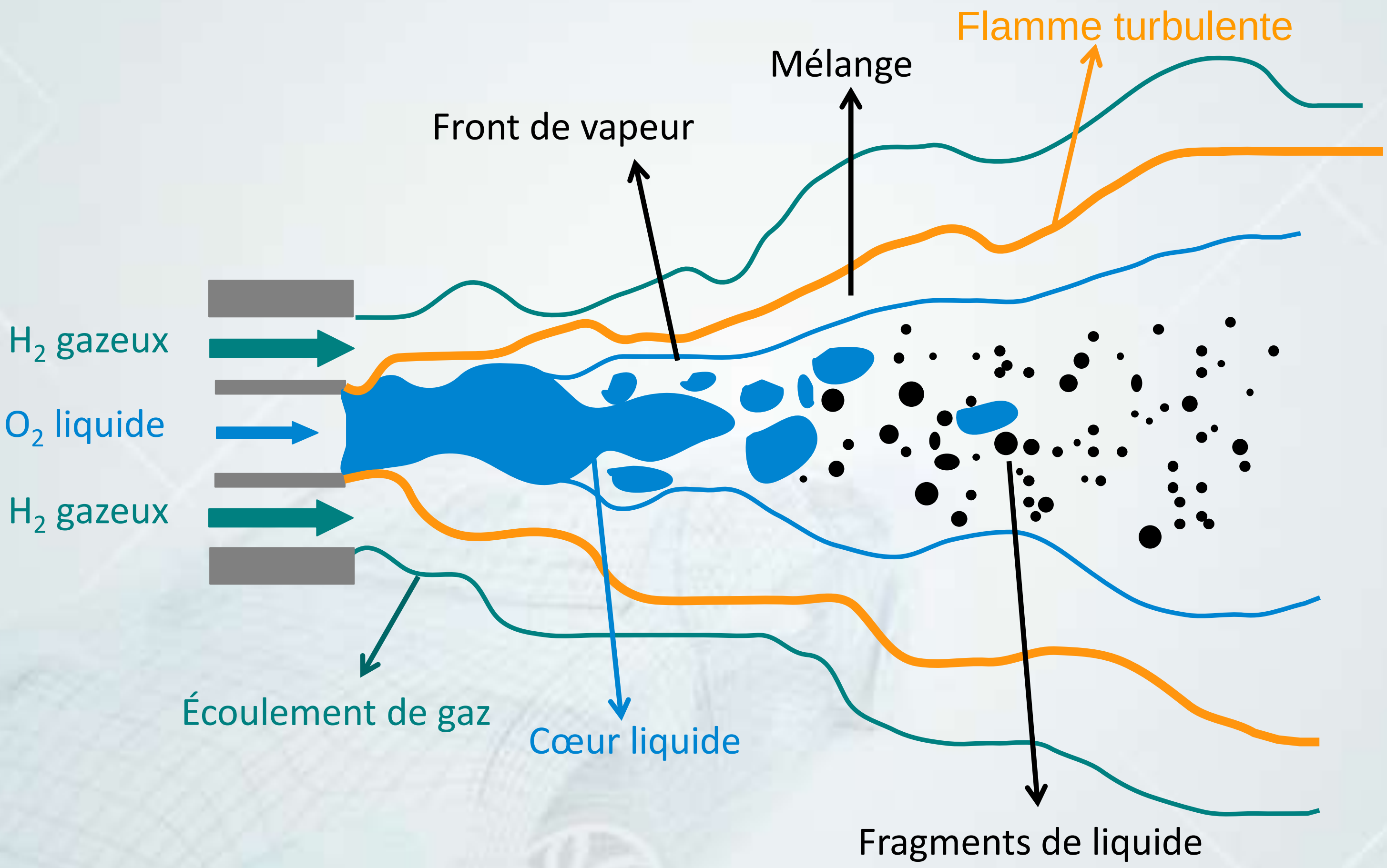
Les sprays et la combustion

Structure du spray – exemple de l'atomisation haute pression

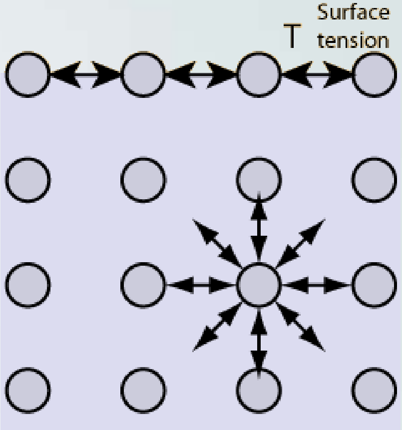


Les sprays et la combustion

Structure du spray – exemple de l’atomisation assisté par air



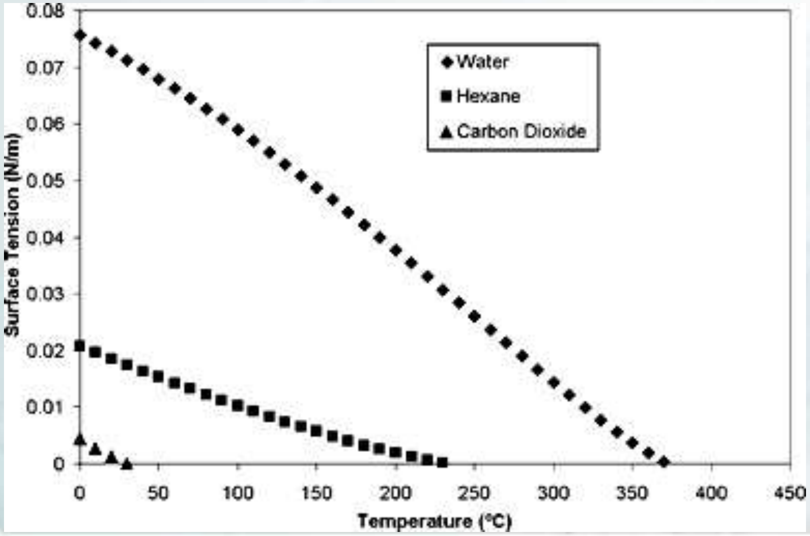
Mécanismes de pulvérisation/atomisation

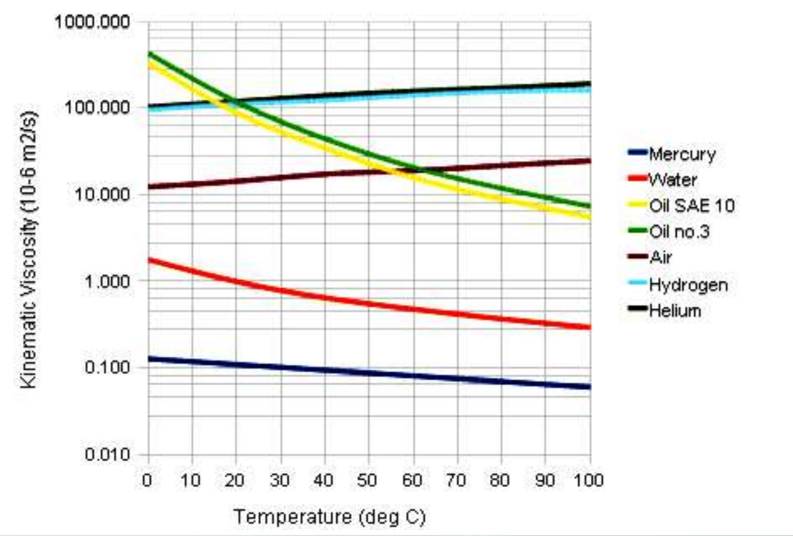


Rompre le continuum liquide

Viscosité et tension superficielle

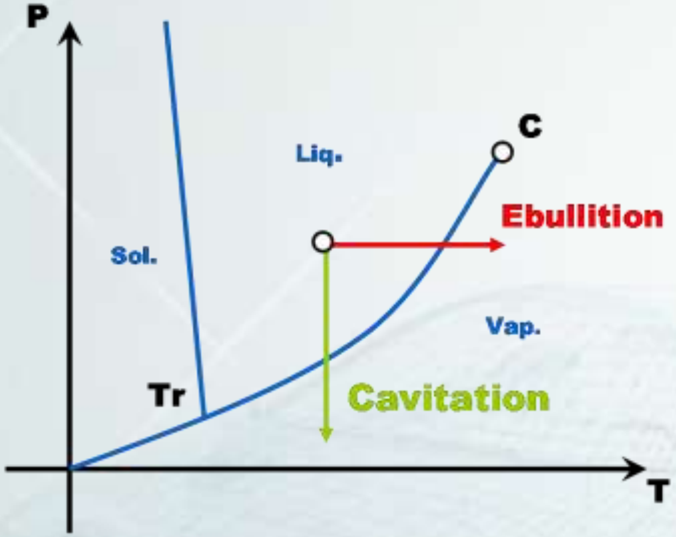
! Température

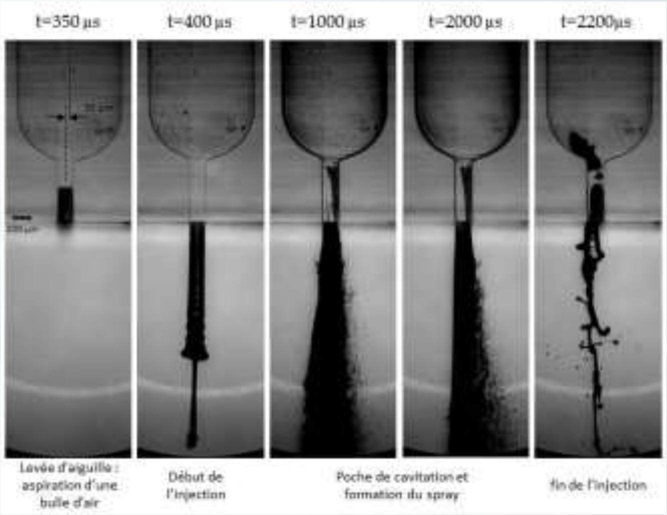




Mécanismes de pulvérisation/atomisation

Cavitation





Loïc Méès , LMFA

Mécanismes de pulvérisation/atomisation

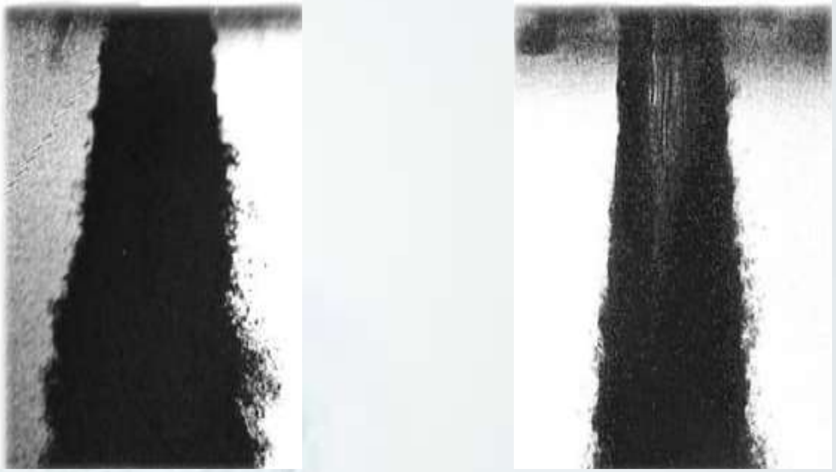
Cavitation : formation de poche de vapeur dans le liquide

Nombre de cavitation :

$$N = \frac{P_{inj} - P_{sat}}{\Delta P}$$

P_{inj} : pression d'injection
P_{sat} : pression de vapeur saturante
ΔP : différence de pression amont et aval

Influence de la cavitation dans l'injecteur sur l'atomisation primaire



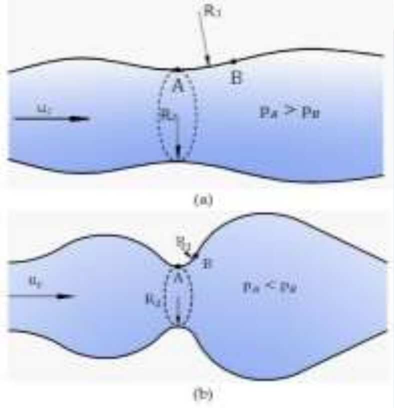
Injecteur cavitant

Injecteur non cavitant

R. Marcer*, P. Le Cottier, H. Chaves, B. Argueyreolles, C. Habchi et B. Barbeau* "A validated Numerical Simulation of Diesel Injector Flow Using a VOF Method", SAE Technical Paper series N° 2000-01-2932, 2000.

Mécanismes de pulvérisation/atomisation

Instabilités



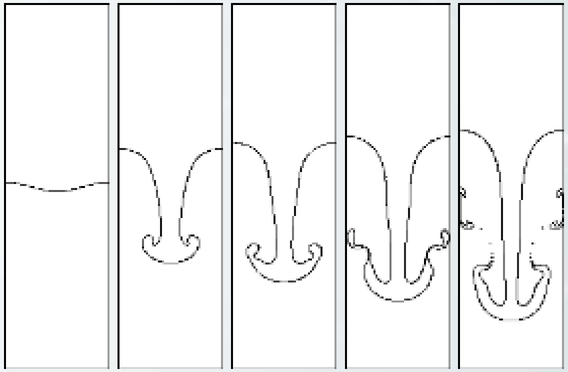
$$\Delta p = \sigma\left[\frac{1}{R_1} + \frac{1}{R_2}\right]$$

Rayleigh (capillaire)

instable (a) :$1/R_2 >> 1/R_1$, stable (b) $1/R_1 >> 1/R_2$ en A

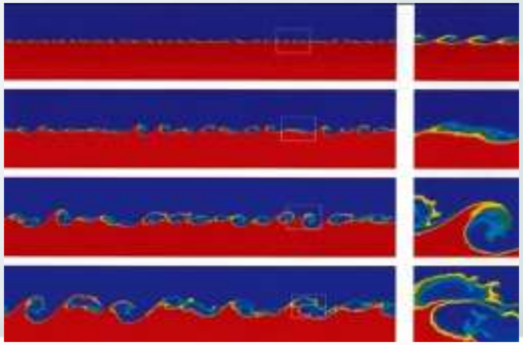
Le liquide est évacué de la zone de déformation, diminuant la section de la zone de déformation et entraînant ainsi une réduction supplémentaire du rayon de courbure. Les effets se conjuguent et s'amplifient mutuellement jusqu'à entraîner la rupture.

Rayleigh-Taylor



instabilité de l'interface séparant deux fluides de densités différentes, qui résulte de la poussée du fluide le plus lourd sur le fluide le plus léger

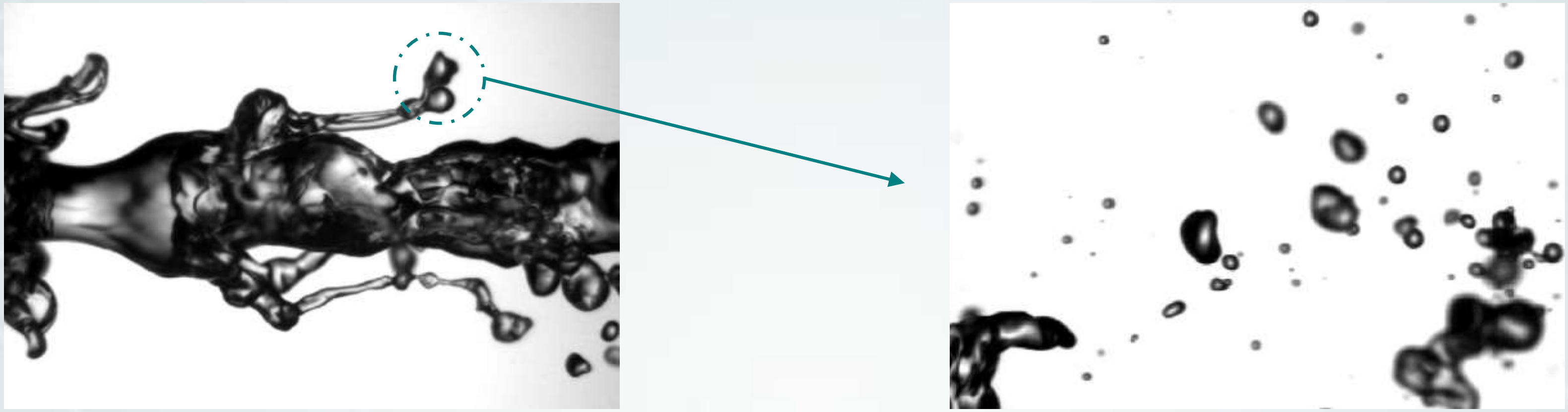
Kelvin-Helmoltz



mouvement ondulatoire qui se forme lorsque deux fluides thermiquement stables sont superposés et se déplacent à des vitesses différentes à leur surface de contact

Mécanismes de pulvérisation/atomisation

Ligamentation : formation de ligament aboutissant à la fragmentation du liquide



Atomisation assistée par air : déstabilisation d’un jet liquide par un courant gazeux D_g=8mm, u_g=35m/s, u_l=0.6m/s

E. Villermaux - Unifying ideas on mixing and atomization. New J. Phys.6(2004)125

Compétition entre frottements aérodynamiques et tension de surface

$$Re = \frac{uL}{\nu}$$

$$We = \frac{\rho u^2 r}{\sigma}$$

$$Oh = \mathrm{Re}^{-1} . We^{0,5}$$

u : échelle de vitesse
L : échelle de longueur
r : échelle de rayon
σ : tension de surface
ρ : masse volumique

Mécanismes de pulvérisation/atomisation

Ligaments – Fragmentation

Cisaillement liquide/gaz ->

instabilité Kelvin-Helmoltz ->

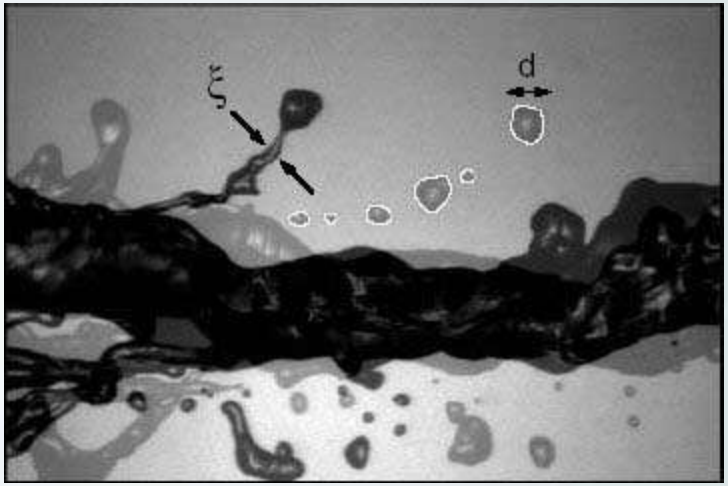
ondes axysimétriques amplifiées ->

instabilité Rayleigh-Taylor transverse ->

ligaments->

instabilité capillaire ->

rupture+coalescence

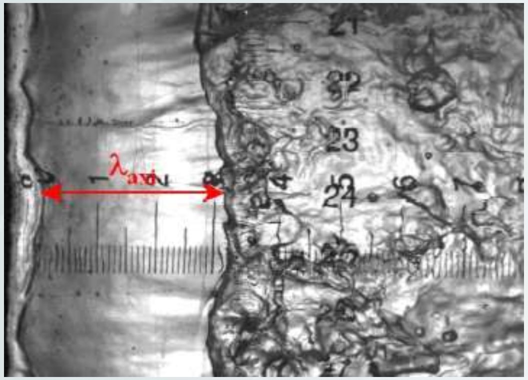


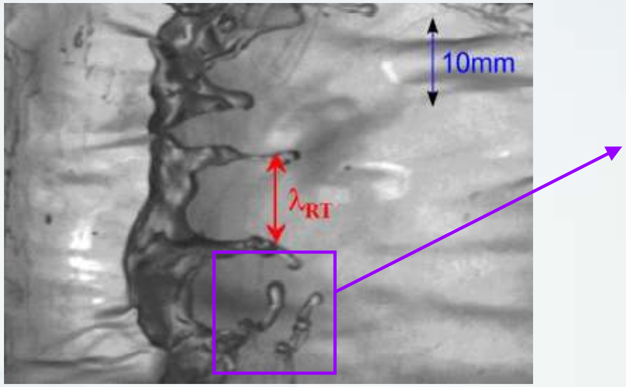
E. Villermaux - Unifying ideas on mixing and atomization. New J. Phys.6(2004)125

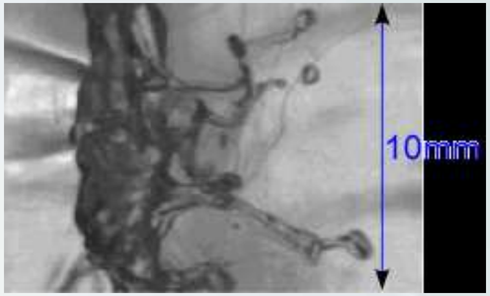
Mécanismes de pulvérisation/atomisation

Instabilités et ondes de surface : mécanisme dans le cadre de l'atomisation assistée par air

Instabilités primaire et secondaire → Formation de gouttes → Atomisation secondaire







Instabilité primaire de type Kelvin-Helmholtz

Thèse de Raynal, 1997

Thèse de Marmottant, 2001

Instabilité secondaire de type Rayleigh-Taylor

Thèse de Hong, 2003

Thèse de Varga, 2003

Thèse de Ben Rayanna, 2007

Rupture de ligaments, large spectre de tailles de 100µm à 1cm dans chaque volume de contrôle

Mécanismes de pulvérisation/atomisation

Instabilité capillaire : instabilités liée à la tension de surface

Classification des régimes en fonction de la vitesse du liquide

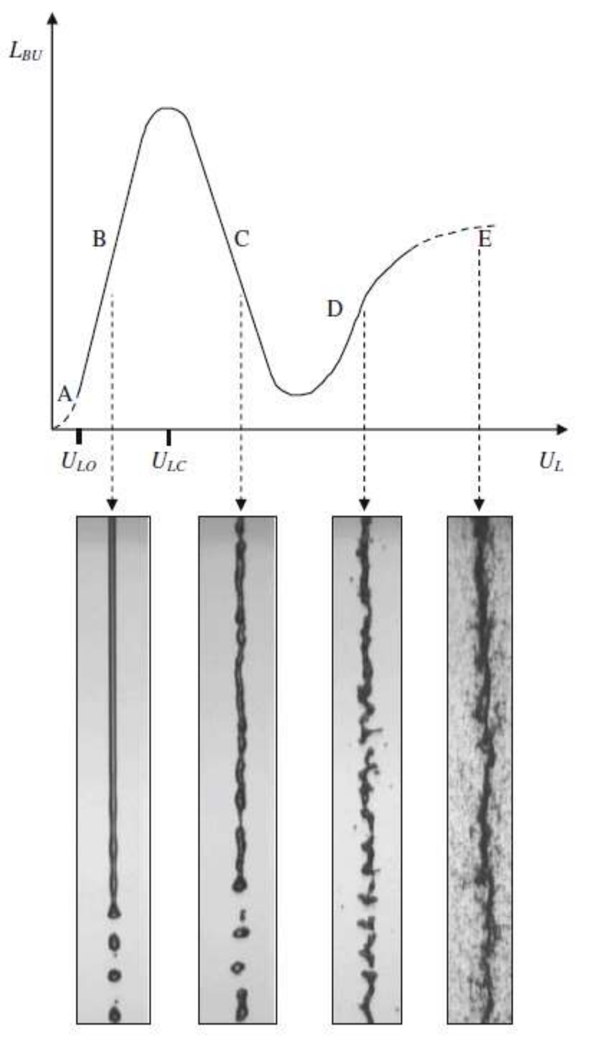
u_l ↗

- A : Ruissellement
- B : Régime de Rayleigh
- C : Régime « first wind-induced »
- D : Régime « second wind-induced »
- E : Régime d’atomisation

Influence sur la longueur de rupture L_{BU}

Leroux S, Dumouchel C, Ledoux M (1996) The stability curve of Newtonian liquid jets. At Sprays 6:623–647

C. Dumouchel (2008) On the experimental investigation on primary atomization of liquid streams. Exp. Fluids



Mécanismes de pulvérisation/atomisation

Atomisation secondaire

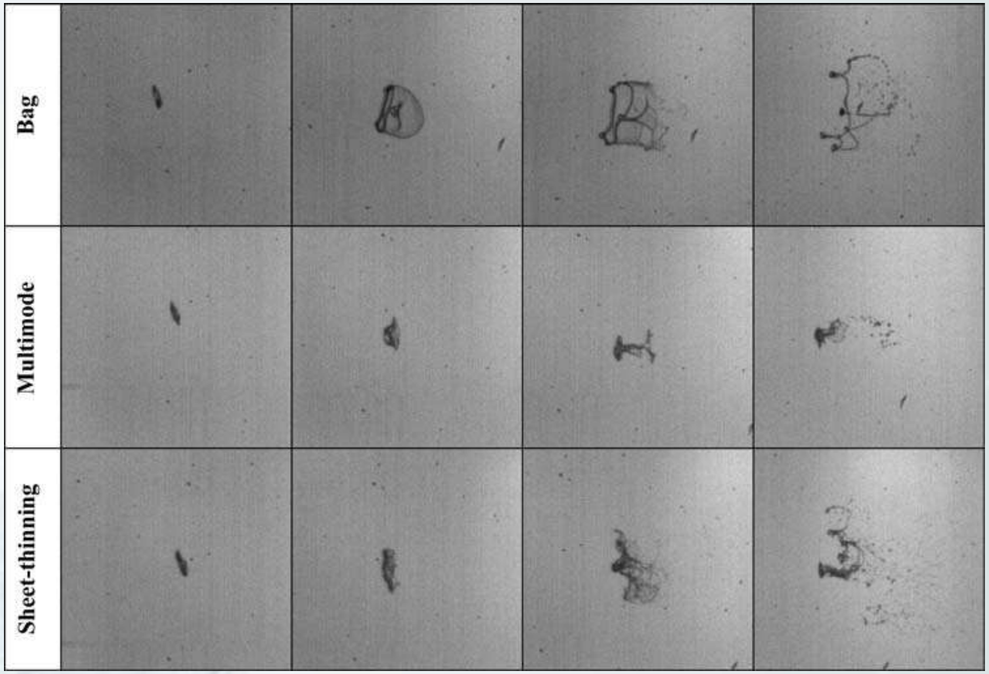
Échelle typique basée sur le nombre de Weber critique We_c

$$d_c = \frac{\sigma We_c}{\rho_g \Delta u^2}$$

- Expérimentalement $We_c \sim 6$
- Δu^2 *est l'échelle d'énergie cinétique*

Différence de vitesse goutte / gaz

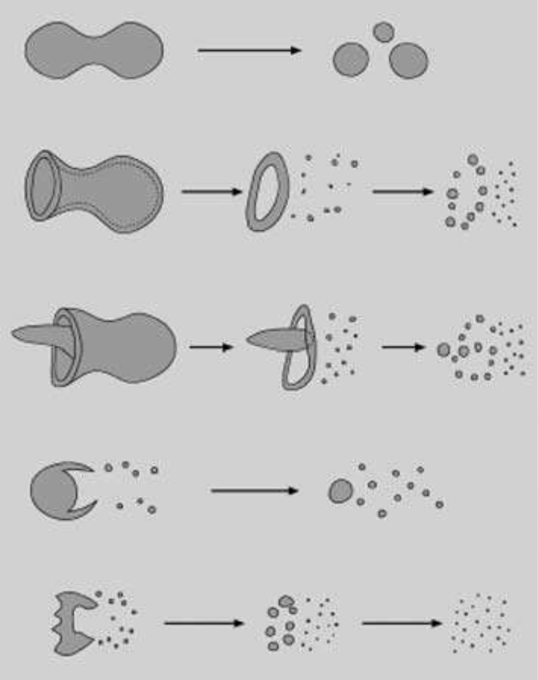
Turbulence gaz

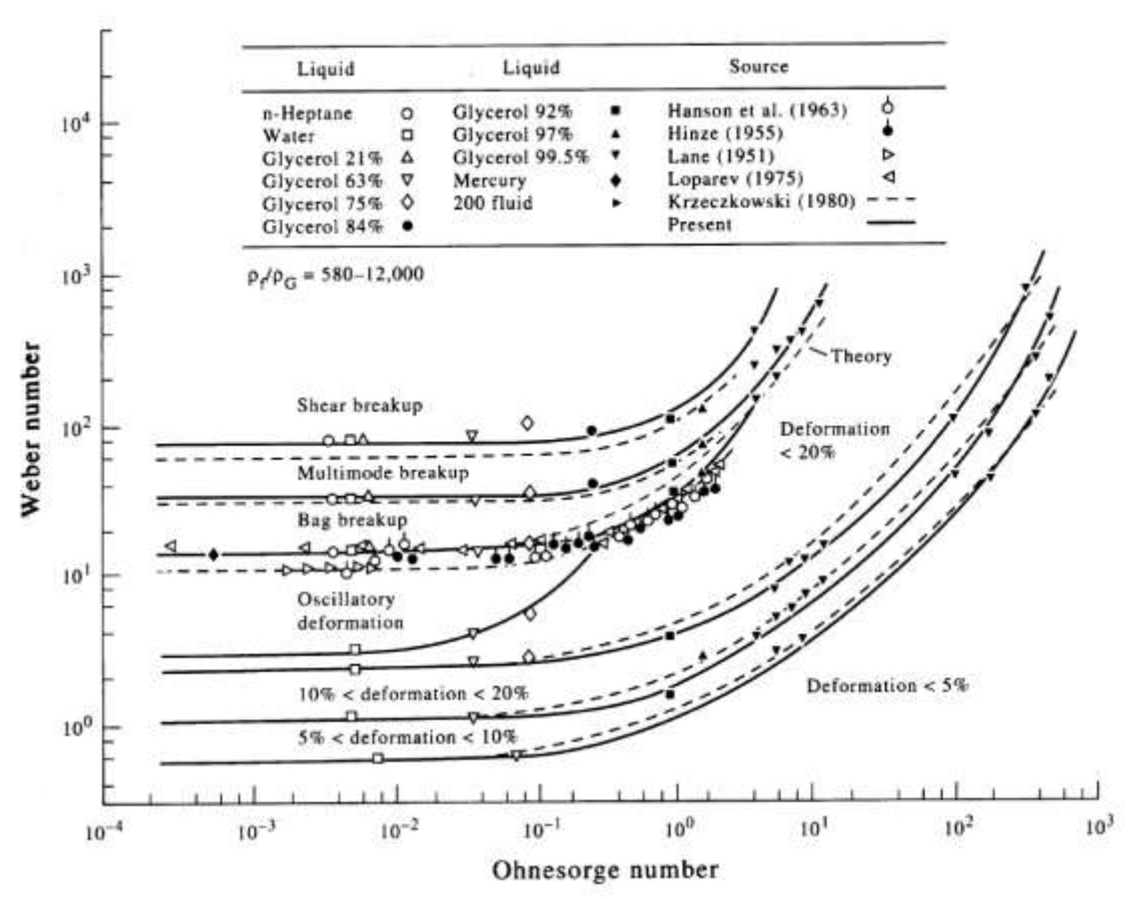


D. R. Guildenbecher, C. López-Rivera,P. E. Sojka- Secondary atomization-Exp Fluids (2009) 46:371–40

Mécanismes de pulvérisation/atomisation

Atomisation secondaire



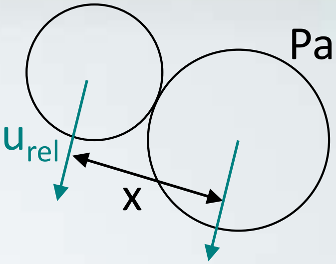


Hsiang LP,Faeth GM (1995) Drop deformation and breakup due to shock wave and steady disturbances. International Journal of Muliphase Flow, vol 21(4):545–560

Mécanismes de pulvérisation/atomisation

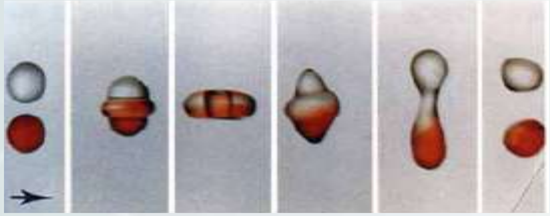
Atomisation secondaire : collisions entre gouttelettes

Ashgriz N. , Poo J.Y. , 1990 : coalescence and separation in binary collisions of liquid drops. *J. Fluid Mech.* 221 , *183-204*

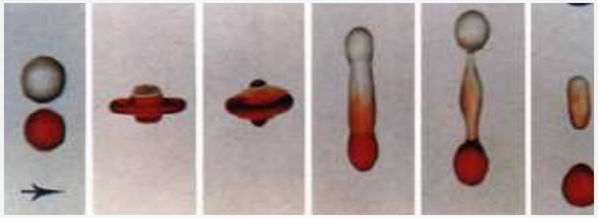


Paramètre d'impact

$$X = \frac{x}{r_1 + r_2}$$



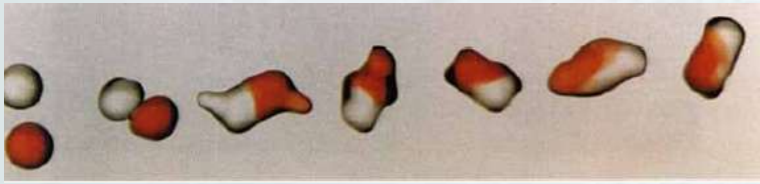
We = 23, Δ = 1, χ = 0.05



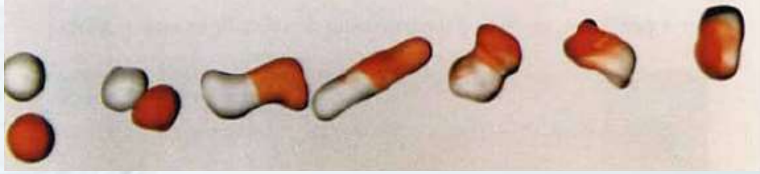
We = 40, Δ = 1, χ = 0

We = 96, Δ = 1, χ = 0

Fragmentations



We = 10, Δ = 1, χ = 0.5



We = 10, Δ = 1, χ = 0.7

Coalescence

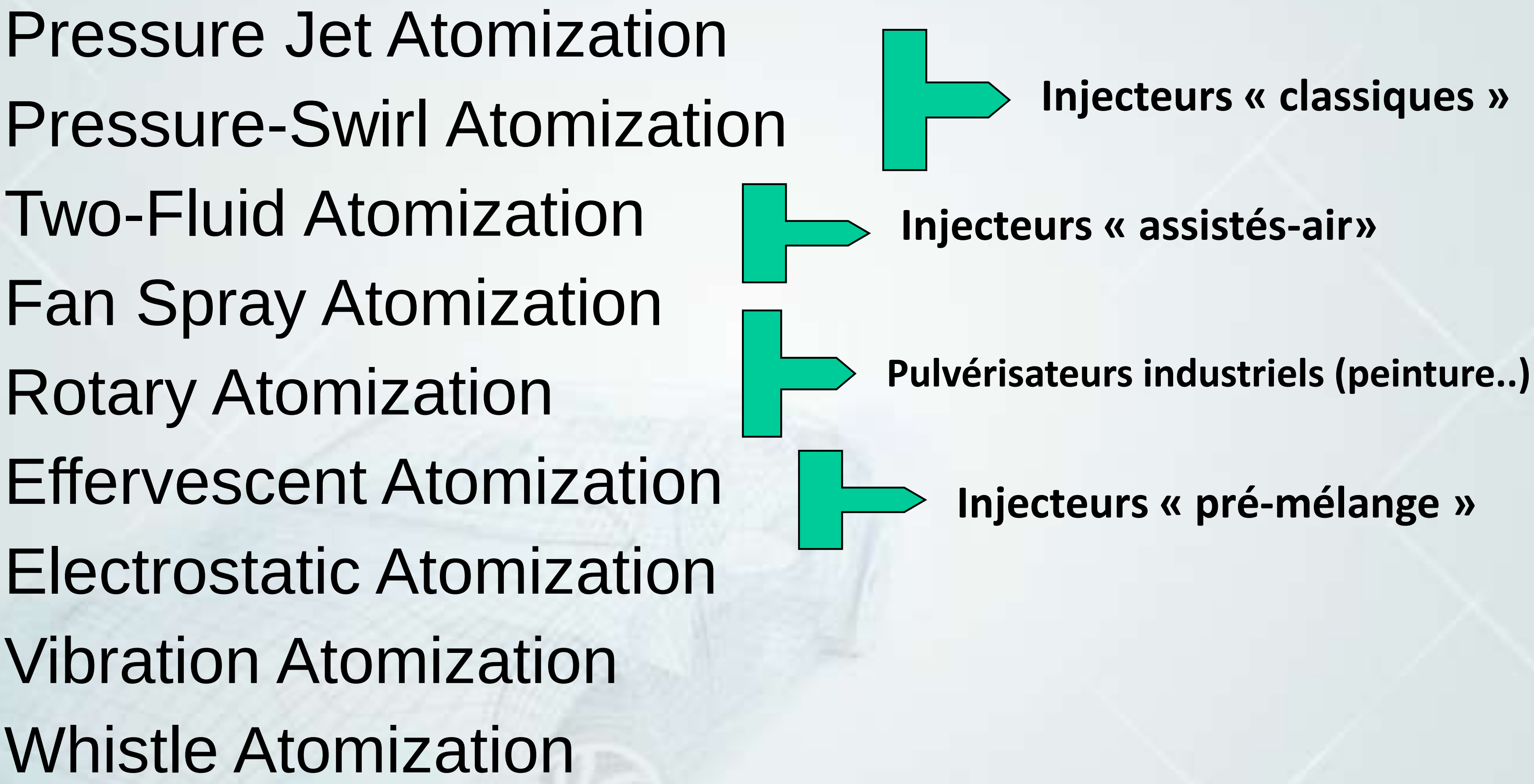
→ Nombre de Weber We
Rapport de taille Δ

→ Mécanisme important dans la zone d'atomisation primaire où on a une forte densité de gouttelettes

Atomiseurs

Method		**Droplet Size (μm)**	**Application**
Pressure Atomization	Plain- Orifice	25–250	Diesel engines, Jet engine afterburners, Ramjets
	Simplex	20–200	Gas turbines, Industrial furnaces
	Duplex	20–200	Gas turbine combustors
	Dual- Orifice	20–200	A variety of aircraft and industrial gas turbines
	Spill Return	20–200	A variety of combustors, Good potential for slurries and fuels of low thermal stability
	Fan Spray	100–1000	High- pressure painting/coat ing, Annular combustors
Rotary Atomization	Spinning Disk	10–200	Spray drying. Aerial distribution of pesticides. Chemical processing
	Rotary Cup	10–320	Spray drying. Spray cooling
Two-Fluid Atomization Air-Assist	Internal Mixing	50–500	Industrial furnaces. Industrial gas turbines
	External Mixing	20–140	Industrial furnaces. Industrial gas turbines
Two-Fluid Atomization Air-Blast	Plain-Jet	15–130	Industrial gas turbines
	Pre- filming	25–140	Wide range of aircraft and industrial gas turbines
Effervescent Atomization		20–340	Combustion
Electrostatic Atomization		0.1–1000	Paint spraying, Printing, Oil burner
Ultrasonic Atomization		1–200	Medical spray. Humidi- fication.Spray drying. Acid etching.Printing circuit. Combustion
Whistle Atomization		~50	Atomization of liquid metals for powder production

Atomisateurs & Pulvériateurs



Pressure Jet Atomization

Pressure-Swirl Atomization

Two-Fluid Atomization

Fan Spray Atomization

Rotary Atomization

Effervescent Atomization

Electrostatic Atomization

Vibration Atomization

Whistle Atomization

Injecteurs « classiques »

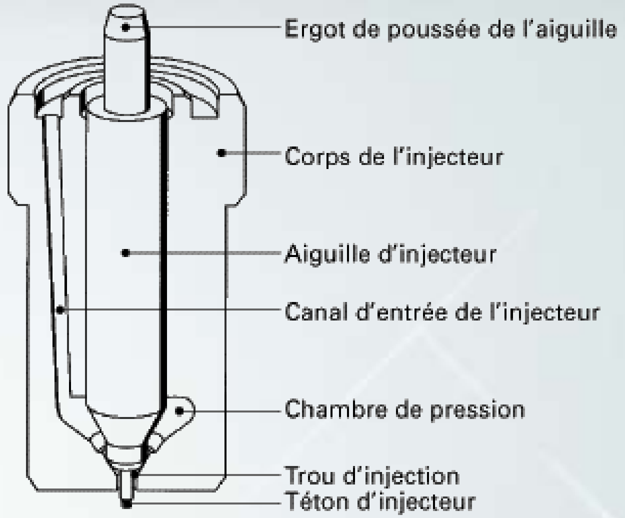
Injecteurs « assistés-air»

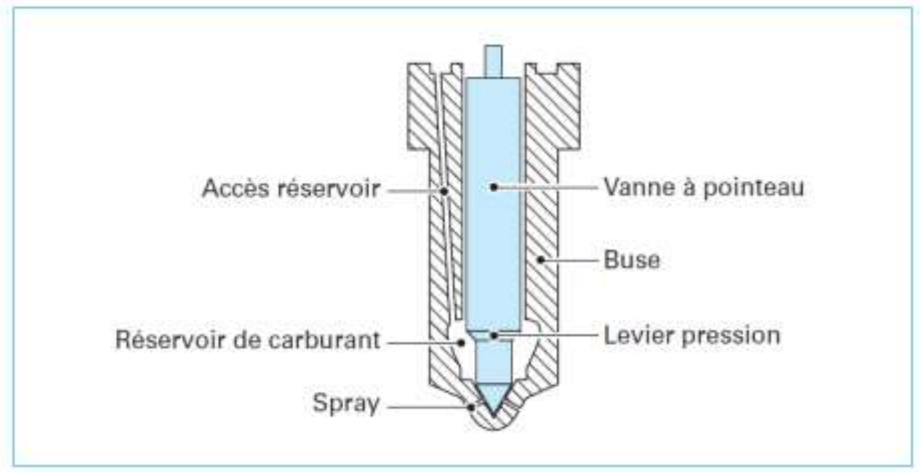
Pulvérisateurs industriels (peinture..)

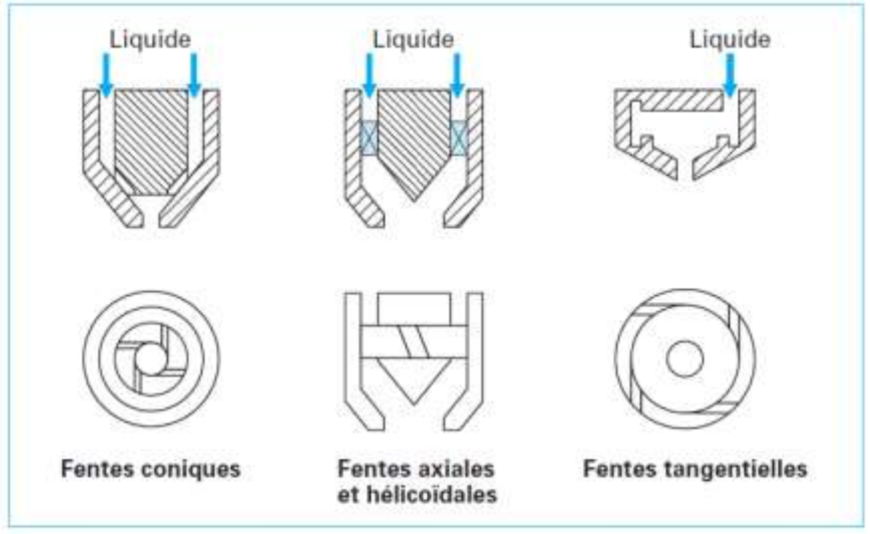
Injecteurs « pré-mélange »

Atomiseurs

Technologie

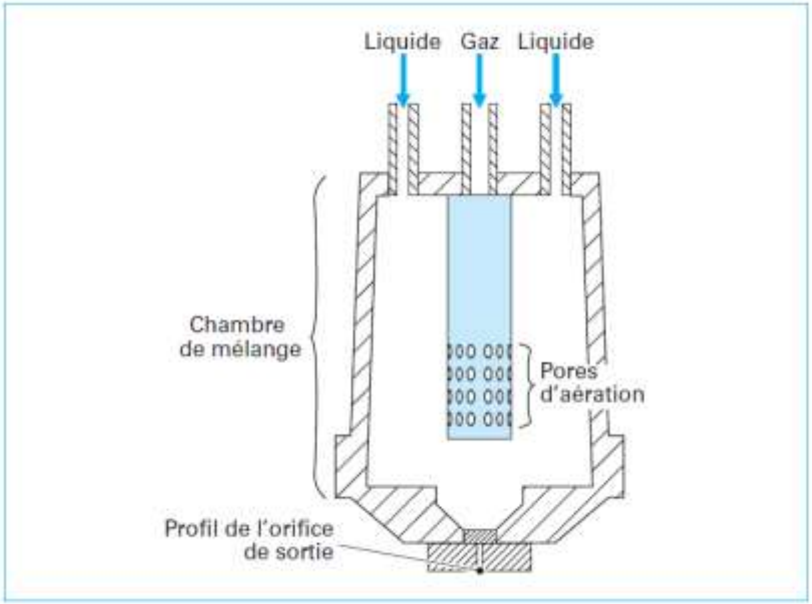


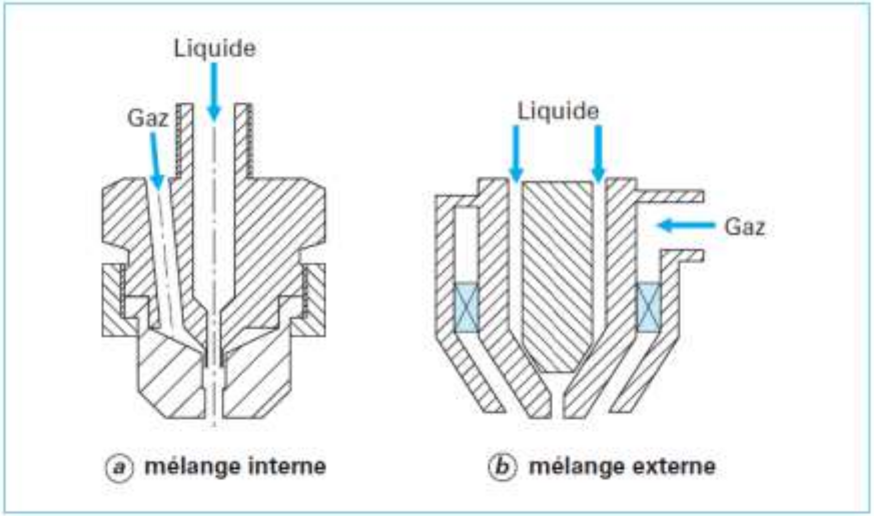


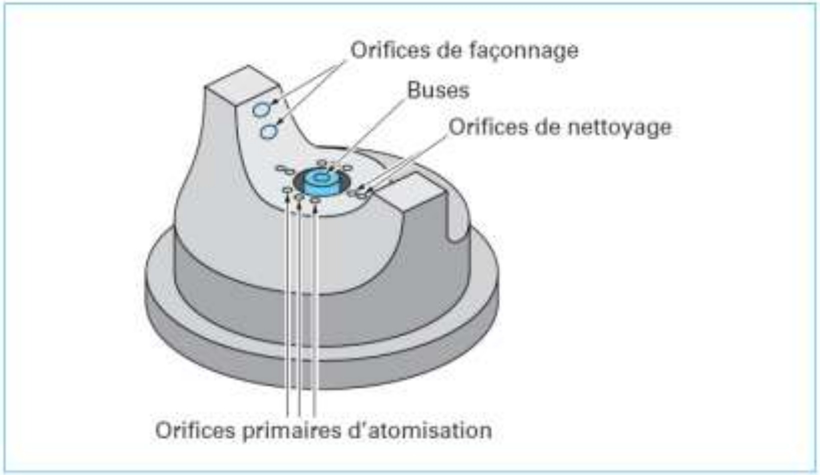


Atomiseurs

Technologie

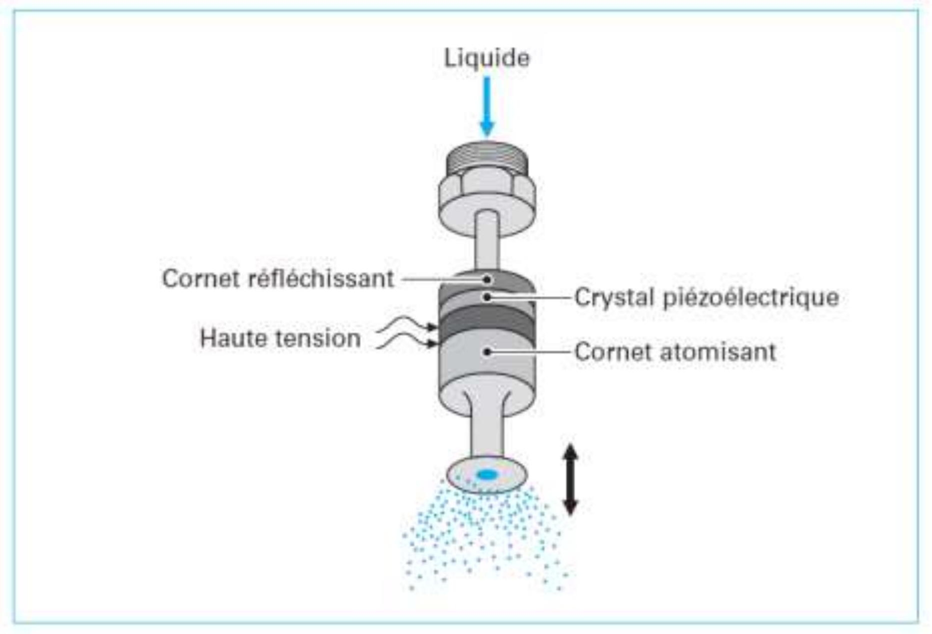


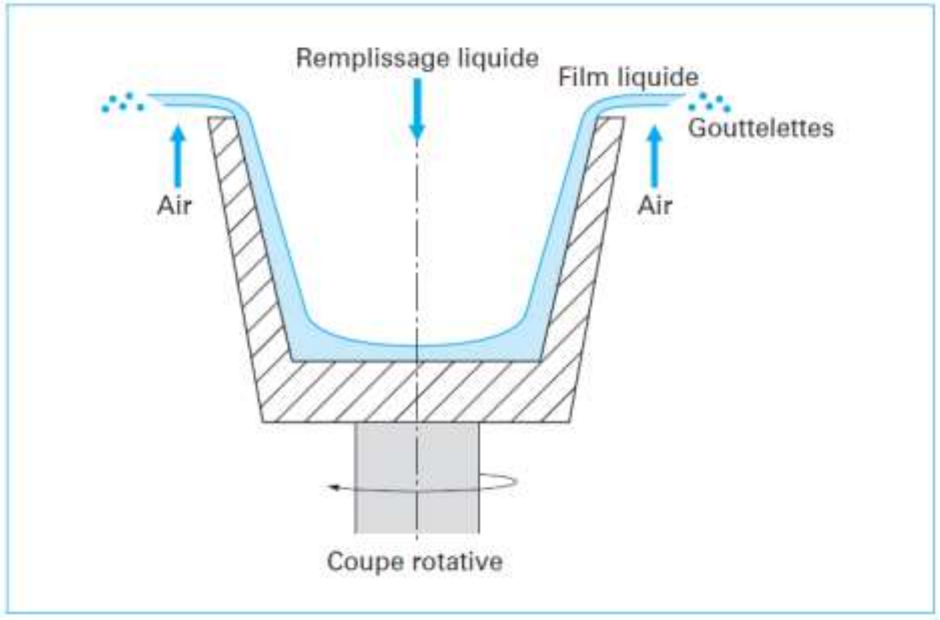




Atomiseurs

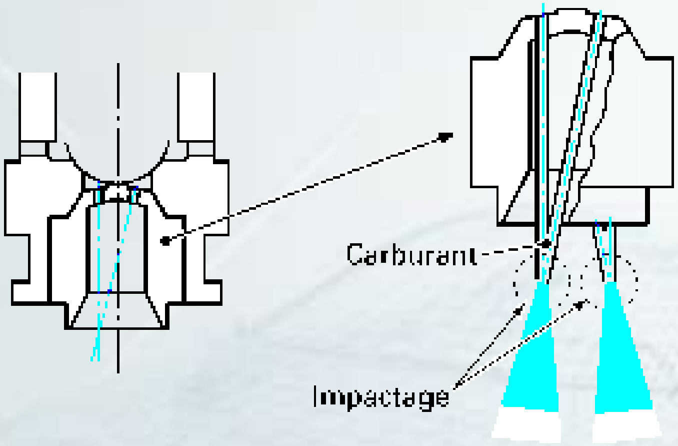
Technologie

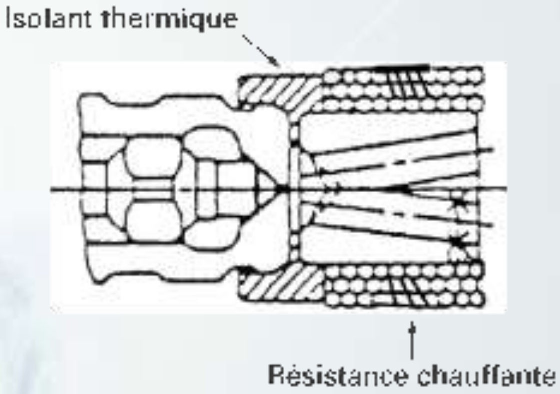




Atomiseurs

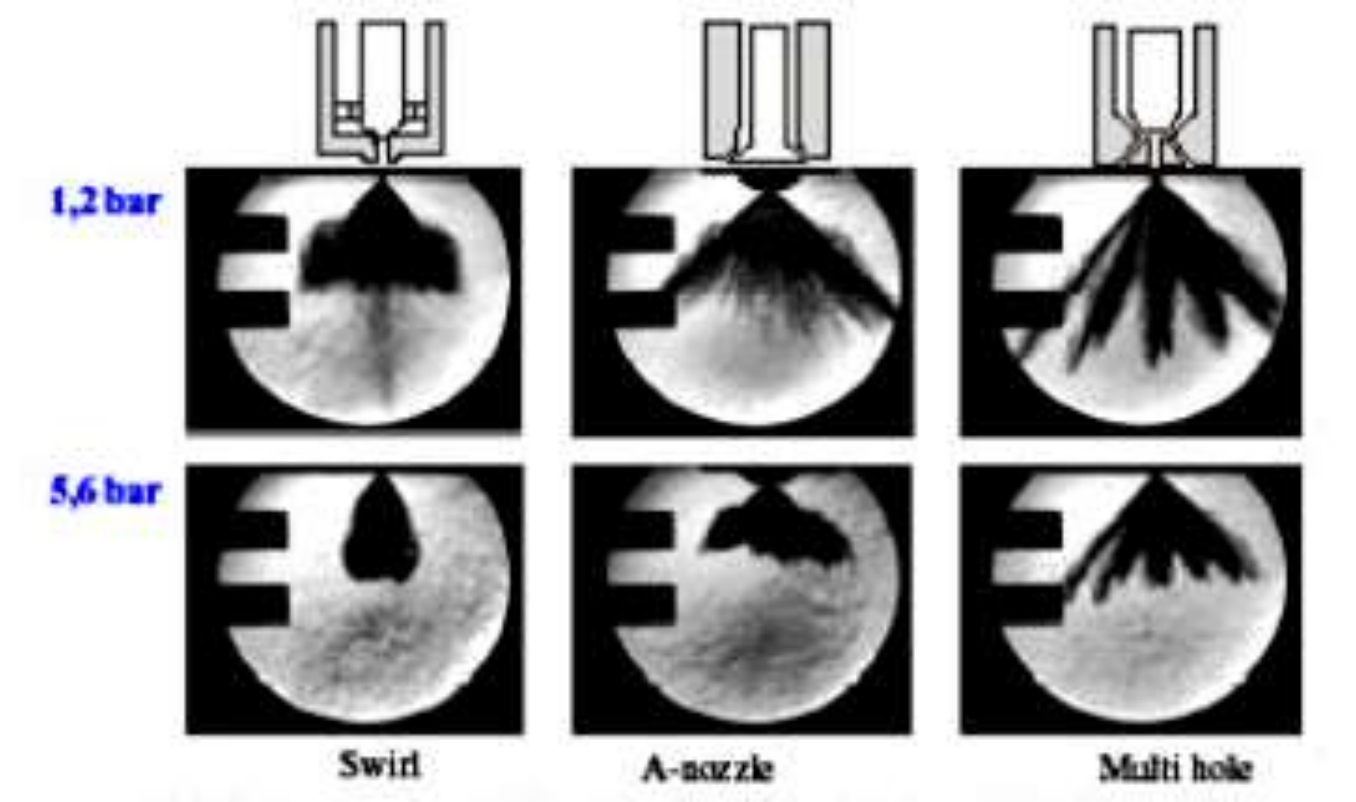
Technologie





Atomiseurs

Technologie



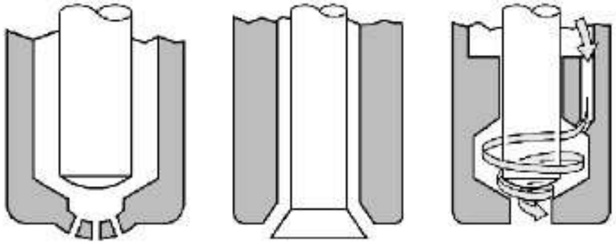
Atomiseurs

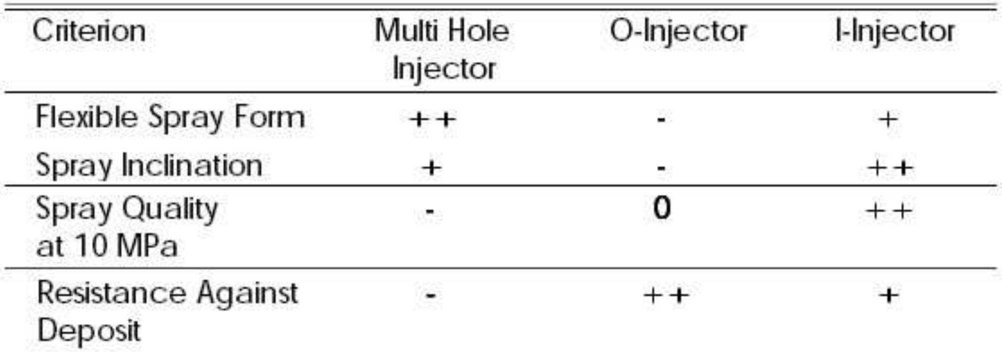
Technologie

Multi-Hole Injector

O-Injector
(Pintle Injector,
Outward Opening)

I-Injector
(Single Hole Injector,
Inward Opening,
With Swirl Component)





Criterion	Multi Hole Injector	O-Injector	I-Injector
Flexible Spray Form	++	-	+
Spray Inclination	+	-	++
Spray Quality at 10 MPa	-	0	++
Resistance Against Deposit	-	++	+

Paramètres d'influence

Pression d'injection

Géométrie buse

Densités

Aérodynamique

Température

Caractéristiques liquide

Paramètres d’influence

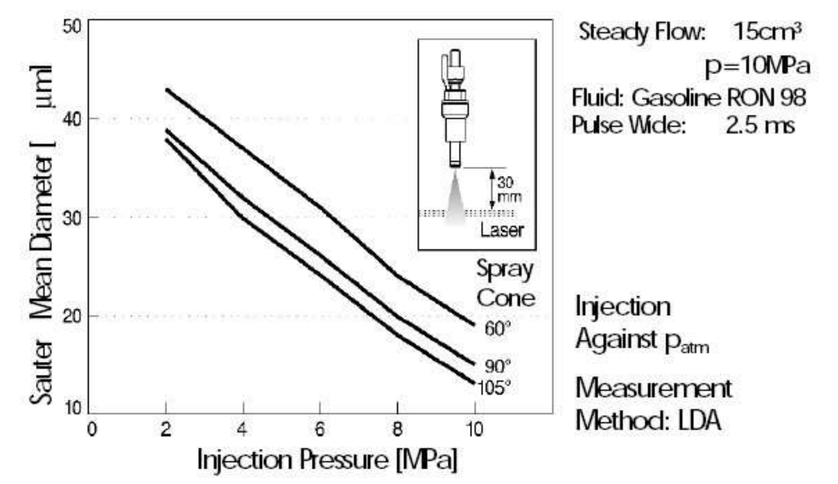
Influence de la pression d’injection

Pi100bar

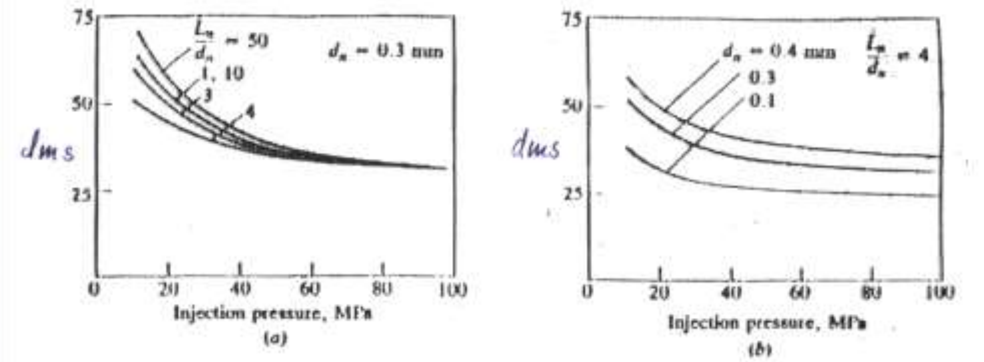
P atm

Pi40bar

P atm



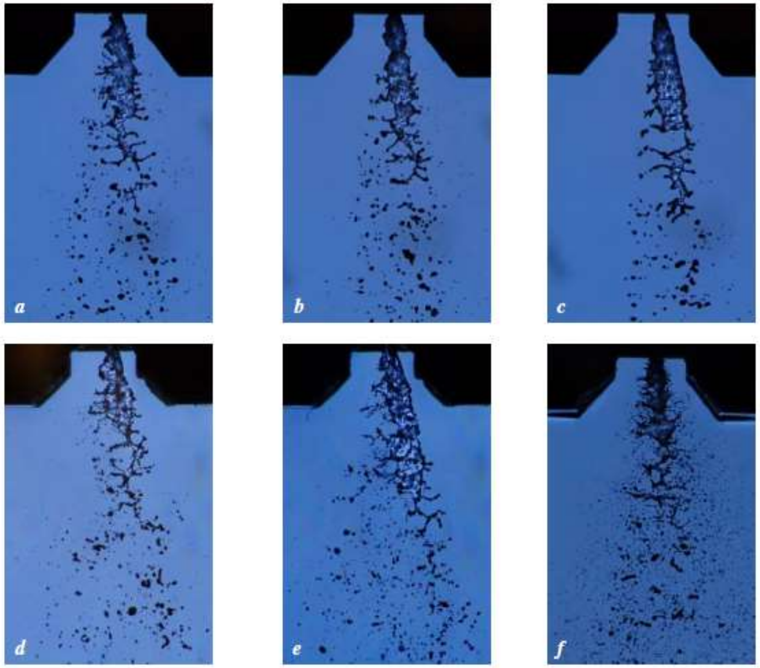
C. Stan, GDI



Heywood, I.C.E fundamentals

Paramètres d'influence

Influence des caractéristiques du liquide

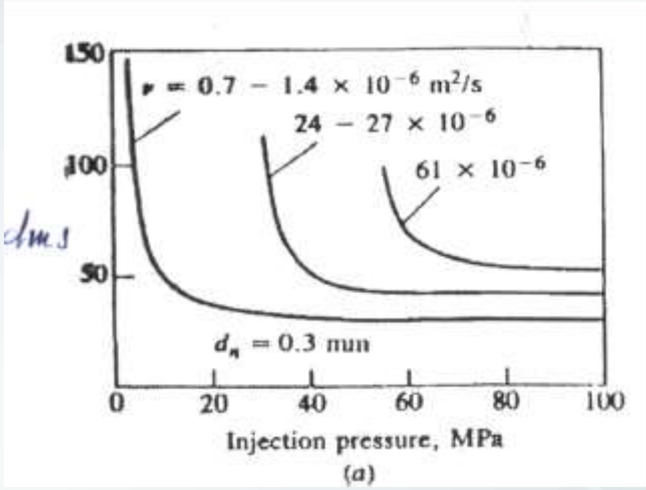


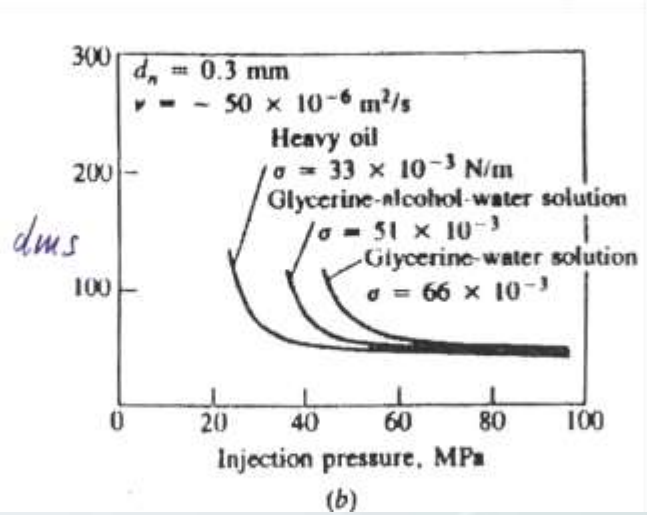
Influence du liquide sur le processus d'atomisation

(a) eau, (b) mélange aqueux de glycérol 5%, (c) mélange aqueux de glycérol 10%, (d) mélange aqueux d'éthanol 1%, (e) mélange aqueux d'éthanol 10%, (f) heptane

($\Delta P_i = 3.5$ bar, $P_{amb} = P_{atm}$)

Thèse de S. Grout 2009 encadrée par C. Dumouchel Analyse multi-échelle des processus d'atomisation et des sprays Application aux injecteurs triple disque

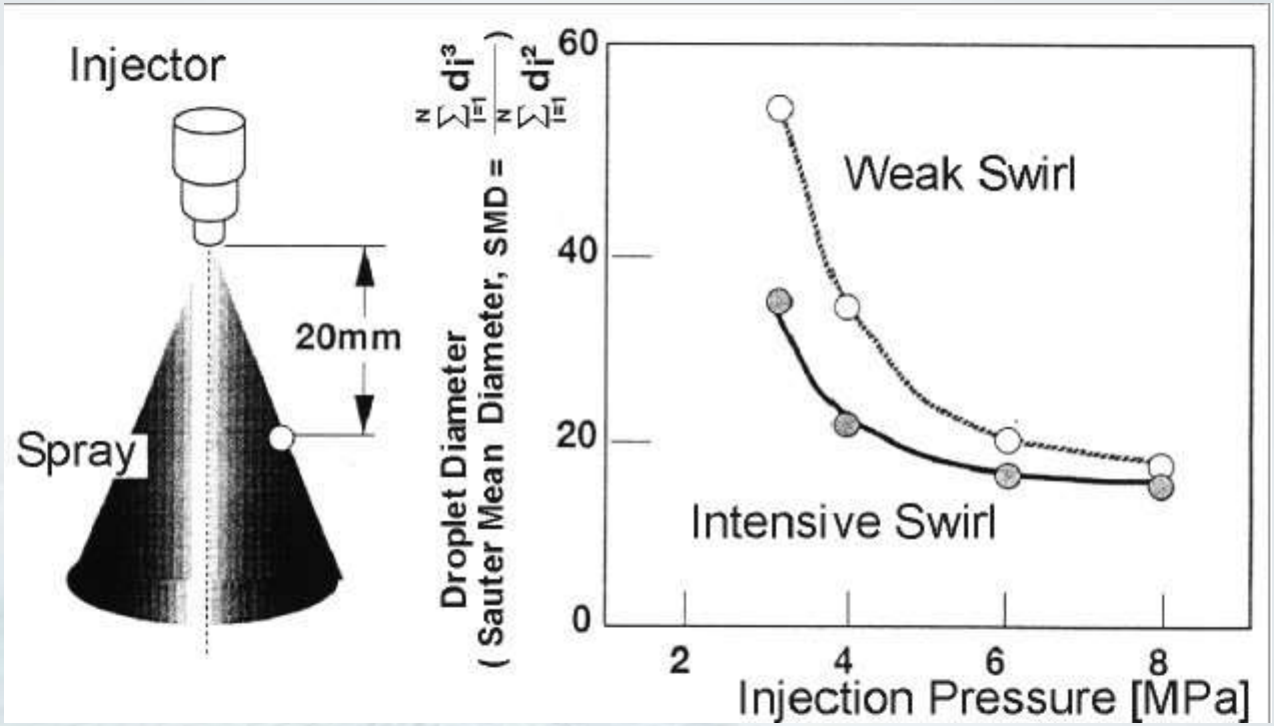




Heywood, I.C.E fundamentals

Paramètres d'influence

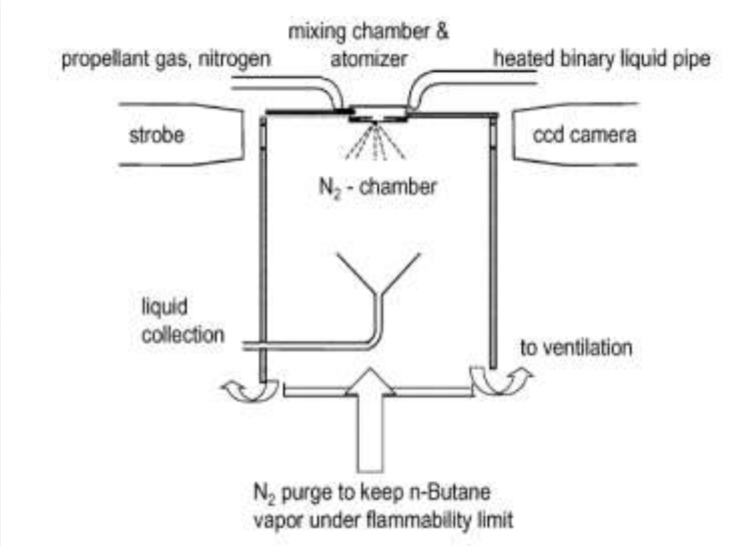
Influence du swirl



C. Stan, GDI

Paramètres d'influence

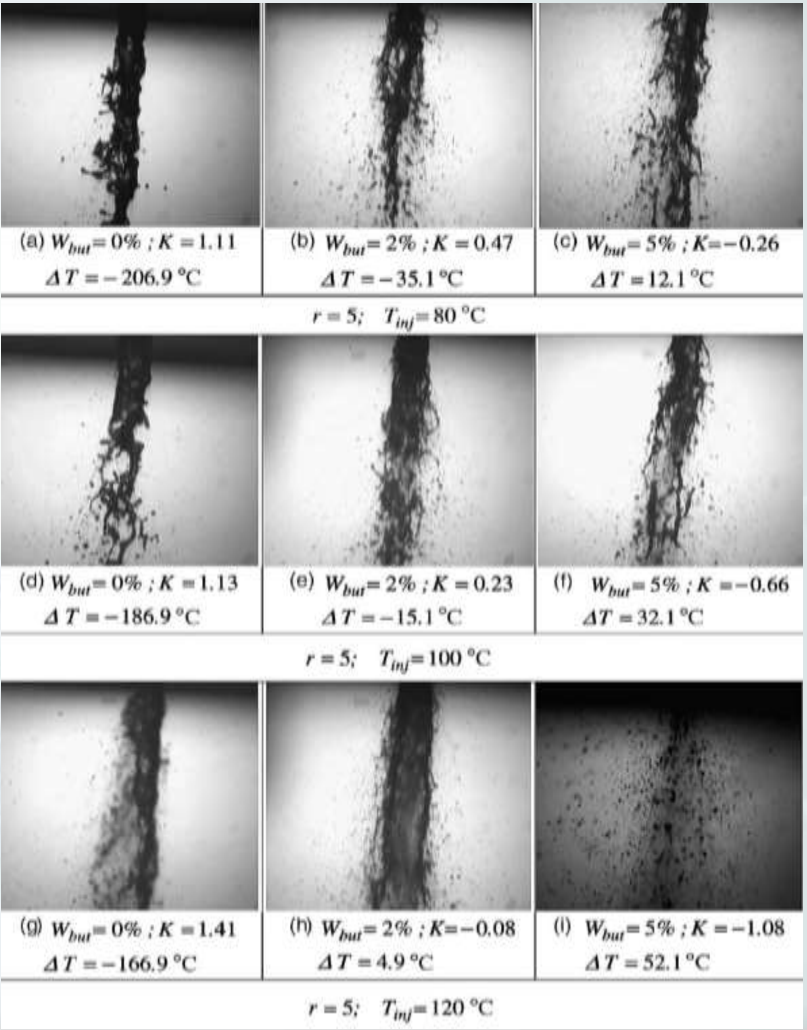
Influence de la Température



Images de spray avec des rapports N_2/liquide r=5

ΔT : Superheat temperature
K : nombre de cavitation

T. Gemci a, K. Yakut a, N. Chigier a,*, T.C. Ho (2004) Experimental study of flash atomization of binary hydrocarbon liquids. J. At. Sprays



(a) $W_{but} = 0\%$; $K = 1.11$ $\Delta T = -206.9$ °C

(b) $W_{but} = 2\%$; $K = 0.47$ $\Delta T = -35.1$ °C

(c) $W_{but} = 5\%$; $K = -0.26$ $\Delta T = 12.1$ °C

$r = 5$; $T_{inj} = 80$ °C

(d) $W_{but} = 0\%$; $K = 1.13$ $\Delta T = -186.9$ °C

(e) $W_{but} = 2\%$; $K = 0.23$ $\Delta T = -15.1$ °C

(f) $W_{but} = 5\%$; $K = -0.66$ $\Delta T = 32.1$ °C

$r = 5$; $T_{inj} = 100$ °C

(g) $W_{but} = 0\%$; $K = 1.41$ $\Delta T = -166.9$ °C

(h) $W_{but} = 2\%$; $K = -0.08$ $\Delta T = 4.9$ °C

(i) $W_{but} = 5\%$; $K = -1.08$ $\Delta T = 52.1$ °C

$r = 5$; $T_{inj} = 120$ °C

Paramètres d’influence

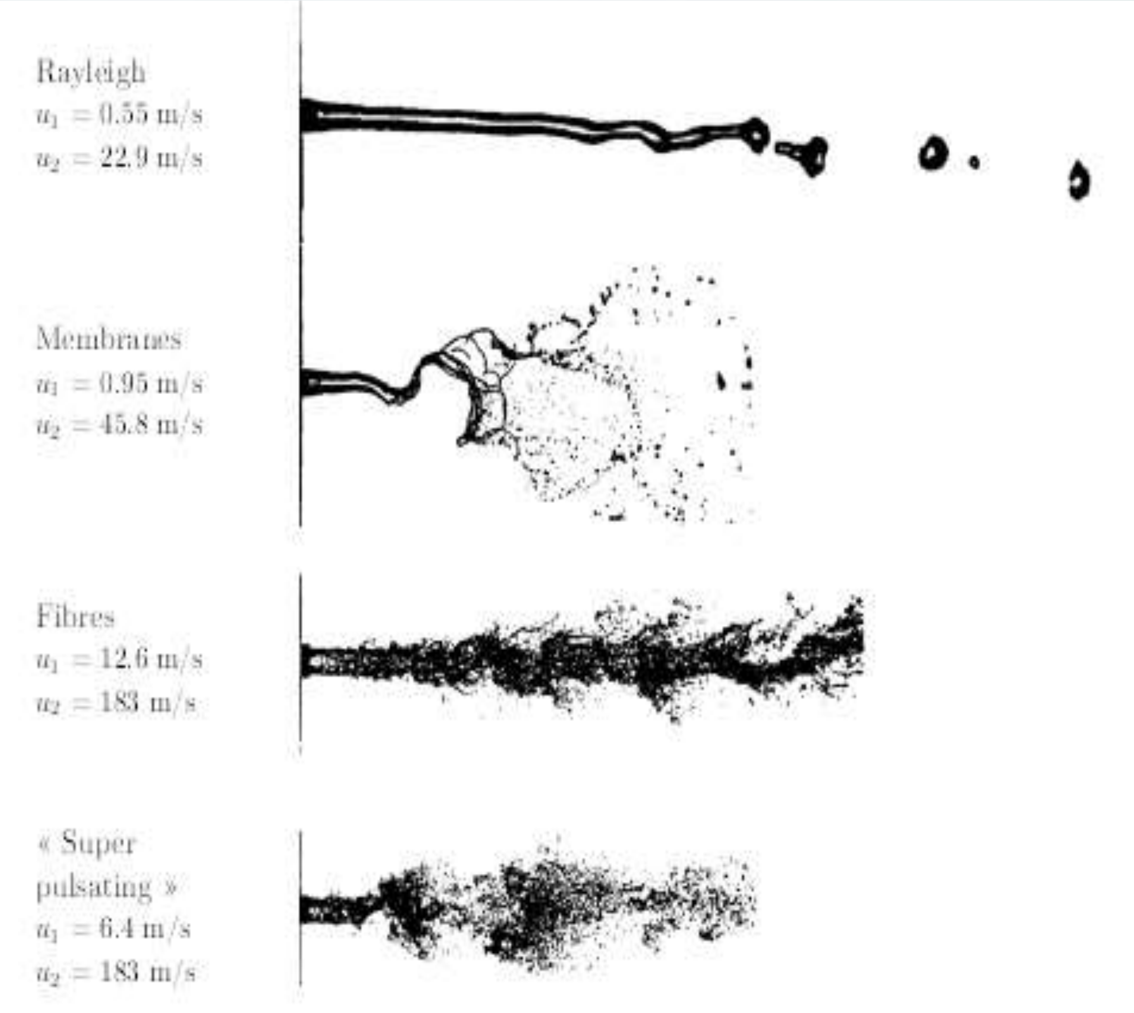
Influence de l’Aerodynamique

Faragó, Z. & Chigier, N. 1992 Morphological classication of disintegration of round liquid jets in a coaxial air stream. Atom. and Sprays 2, 137153.

↓

Classification avec le paramètre *M*

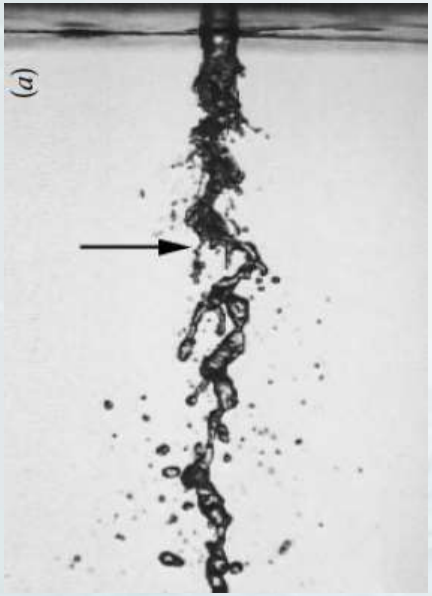
$$M = \frac{\rho_g u_g^2}{\rho_l u_l^2}$$



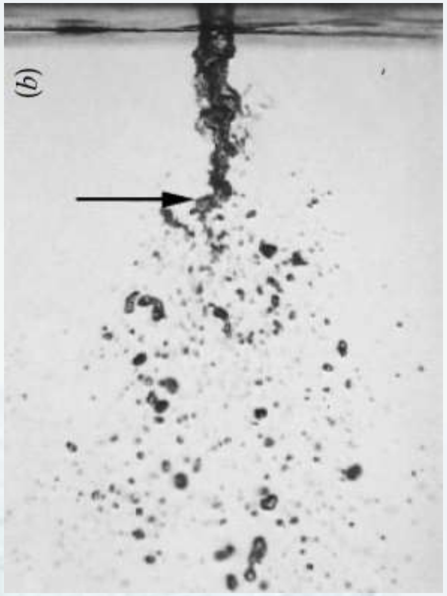
Paramètres d’influence

Influence du paramètre *M* sur la longueur de rupture

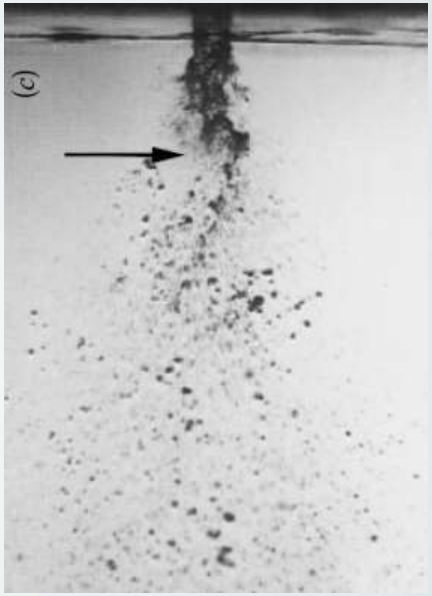
Lasheras, J., Villermaux, E. & Hopfinger, E. 1998 Breakup and atomisation of a round water jet by a high-speed annular jet. J. Fluid Mech. 357, 351379.



$M = 2,5$



$M = 10$



$M = 40$

→ Corrélations basées sur ce paramètres

Paramètres d'influence

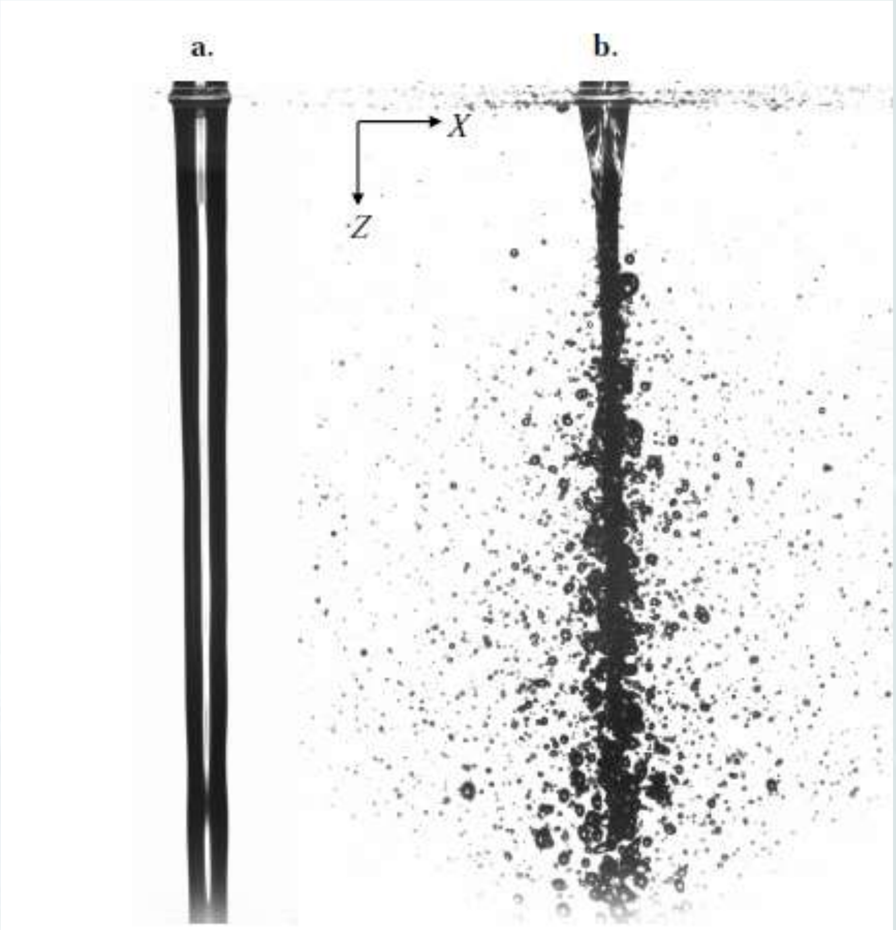
Influence de l'acoustique

G.Boisdron (2006) Etude de l'atomisation d'un jet liquide assisté par air soumis à une onde acoustique stationnaire transverse haute fréquence. Thèse de doctorat

Rel = 3715
We = 1,3
$P_{ac} = 2448$ *Pa*

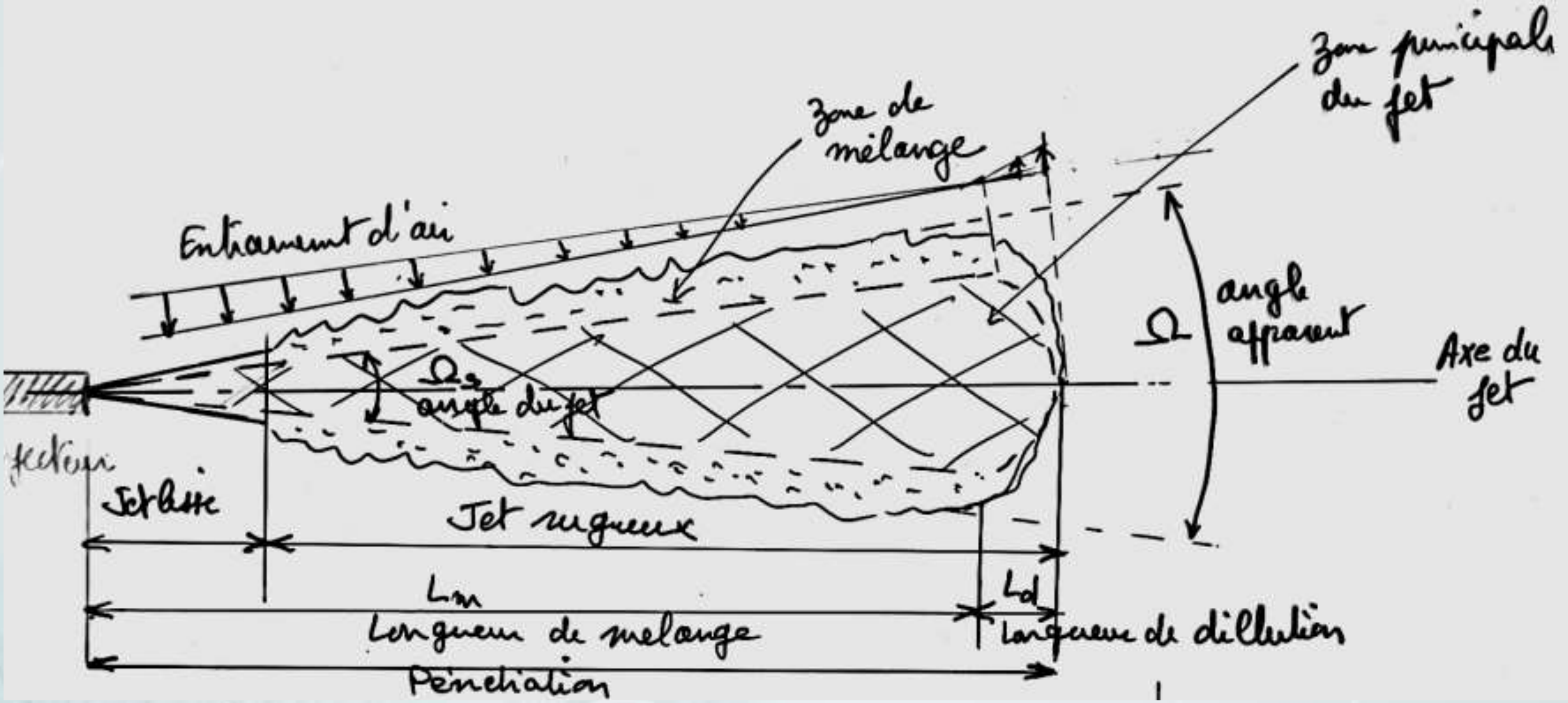
a : sans acoustique

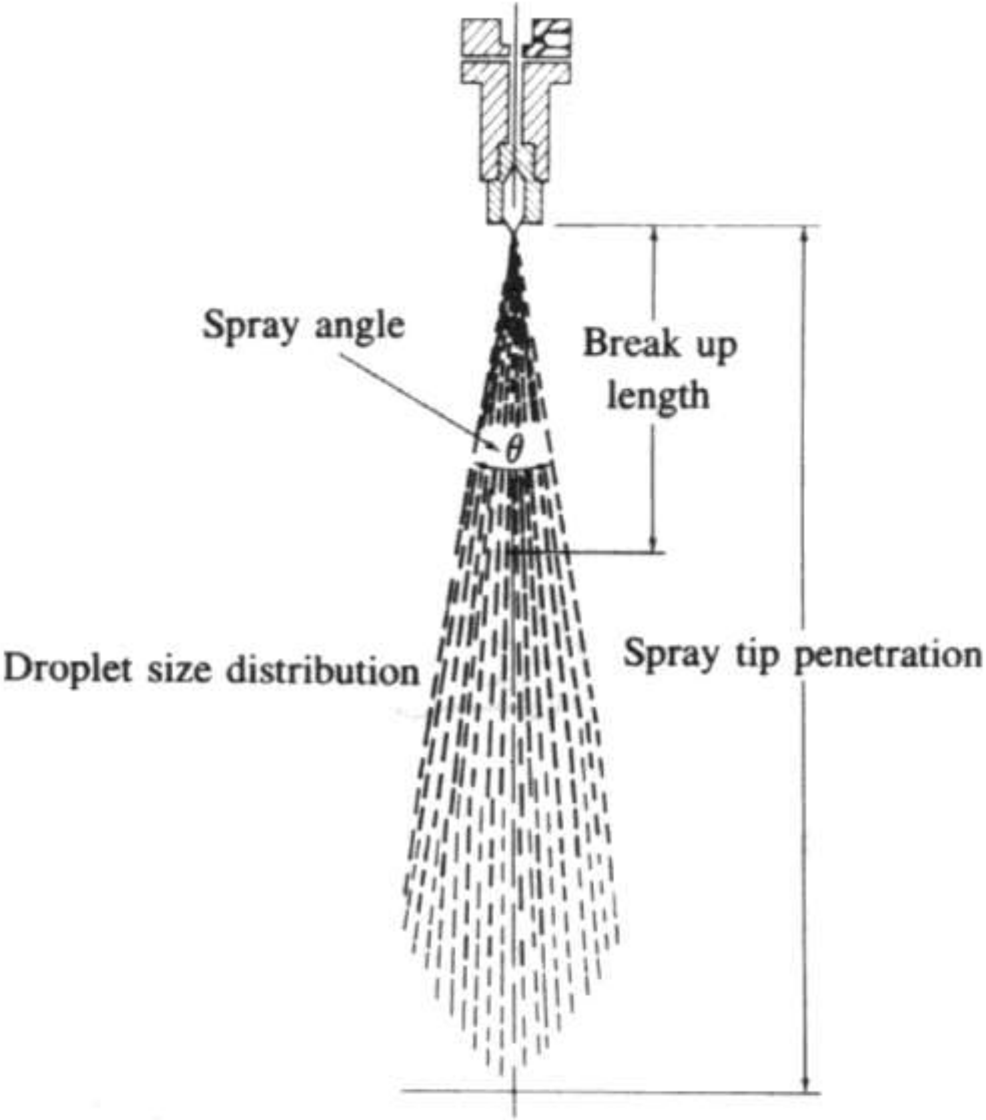
b : avec une onde acoustique transverse d'amplitude de pression acoustique P_{ac}

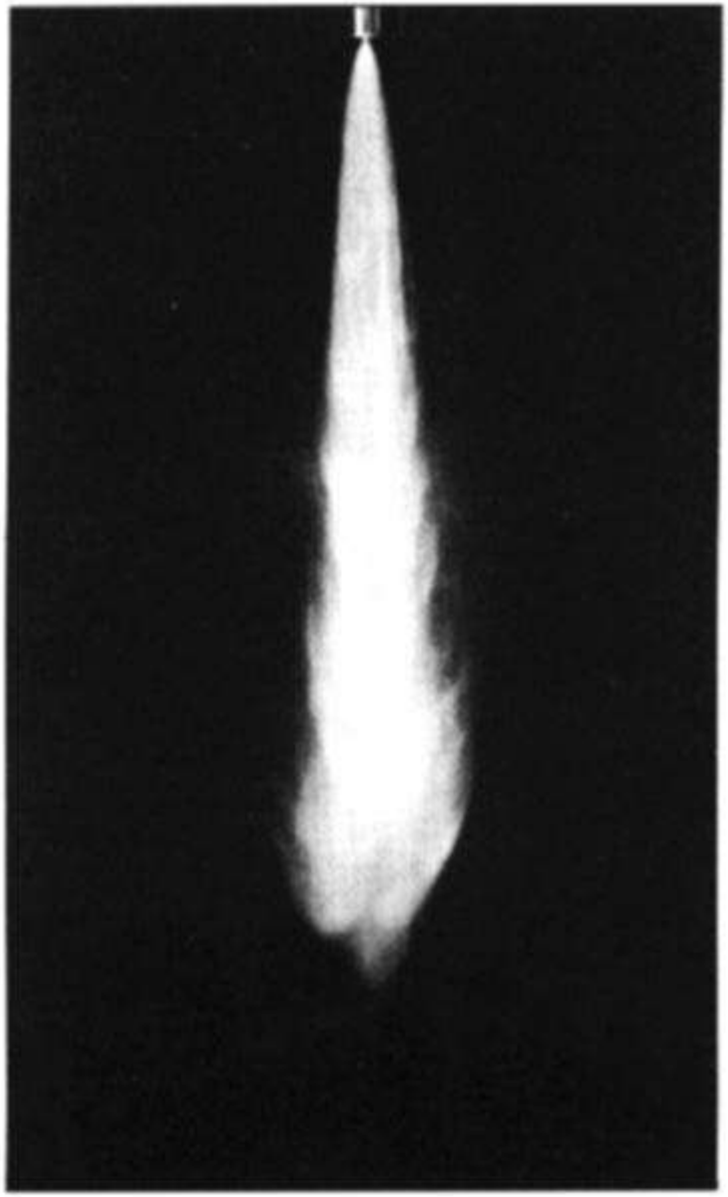


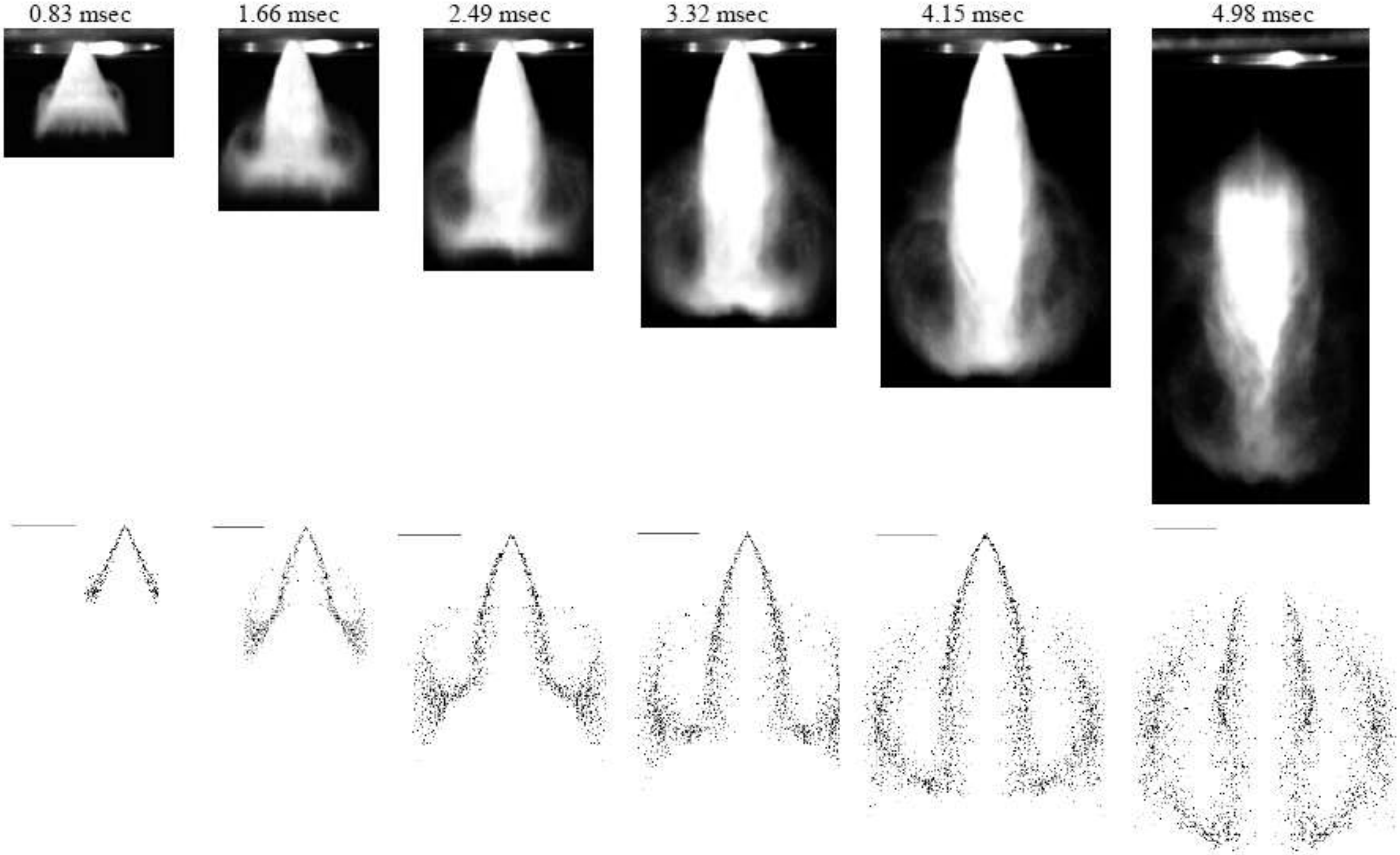
Caractérisation des sprays

Angle, pénétration, longueur liquide,…




Spray angle
θ
Break up length
Spray tip penetration
Droplet size distribution




0.83 msec

1.66 msec

2.49 msec

3.32 msec

4.15 msec

4.98 msec

Caractérisation des sprays

Distributions de tailles

Normale

$$f(d) = \frac{\delta N}{\delta d} = \frac{1}{s\sqrt{2\pi}} e^{\frac{1}{2s^2}(d-\bar{d})^2}$$

Log-normale

$$f(d) = \frac{\delta N}{\delta d} = \frac{1}{sd\sqrt{2\pi}} e^{-\frac{1}{2s^2}(\ln d - \ln \bar{d})^2}$$

Nukiyama-Tanasawa

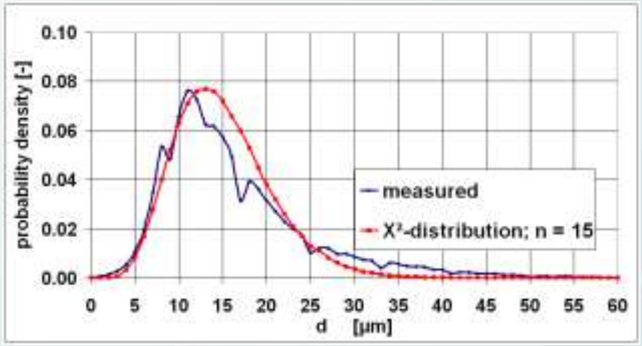
$$f(d) = \frac{\delta N}{\delta d} = a d^{p} e^{-b d^{q}}$$

Rosin-Rammler

$$V = 1 - e^{\left(-\frac{d}{X}\right)^{q}}$$

X^2

$$f(d) = \frac{\delta N}{\delta d} = \frac{1}{2^{k/2}\,\Gamma\left(k/2\right)} d^{k/2-1} e^{-d/2}$$



Caractérisation des sprays

Diamètres moyens

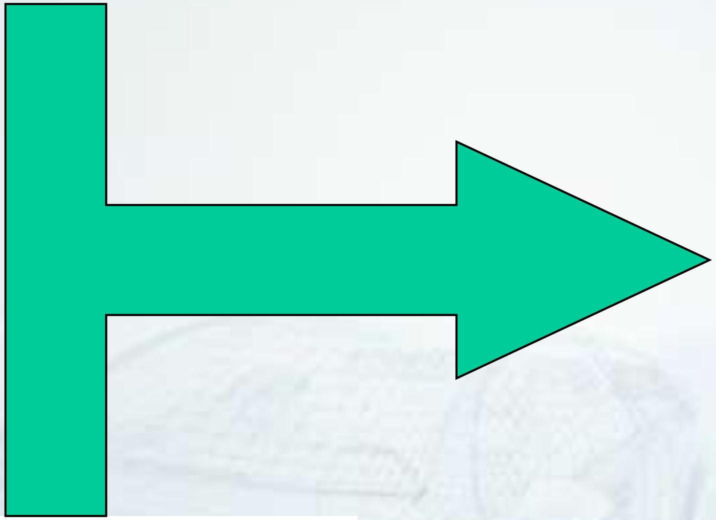
$$d_{ab} = \left[\frac{\int_{d_{min}}^{d_{max}} d^a \left(\frac{\delta N}{\delta d} \right) \delta d}{\int_{d_{min}}^{d_{max}} d^b \left(\frac{\delta N}{\delta d} \right) \delta d} \right]^{\frac{1}{a-b}}$$

$$d_{ab} = \left[\frac{\sum_i N_i d^a}{\sum_i N_i d^b} \right]^{\frac{1}{a-b}}$$

$$D_{10} = \frac{\int_{D_{min}}^{D_{max}} D(dN/dD)dD}{\int_{D_{min}}^{D_{max}} (dN/dD)dD}$$

$$D_{20} = \left[\frac{\int_{D_{min}}^{D_{max}} D^2 (dN/dD)dD}{\int_{D_{min}}^{D_{max}} (dN/dD)dD} \right]^{1/2}$$

$$D_{30} = \left[\frac{\int_{D_{min}}^{D_{max}} D^3 (dN/dD)dD}{\int_{D_{min}}^{D_{max}} (dN/dD)dD} \right]^{1/3}$$



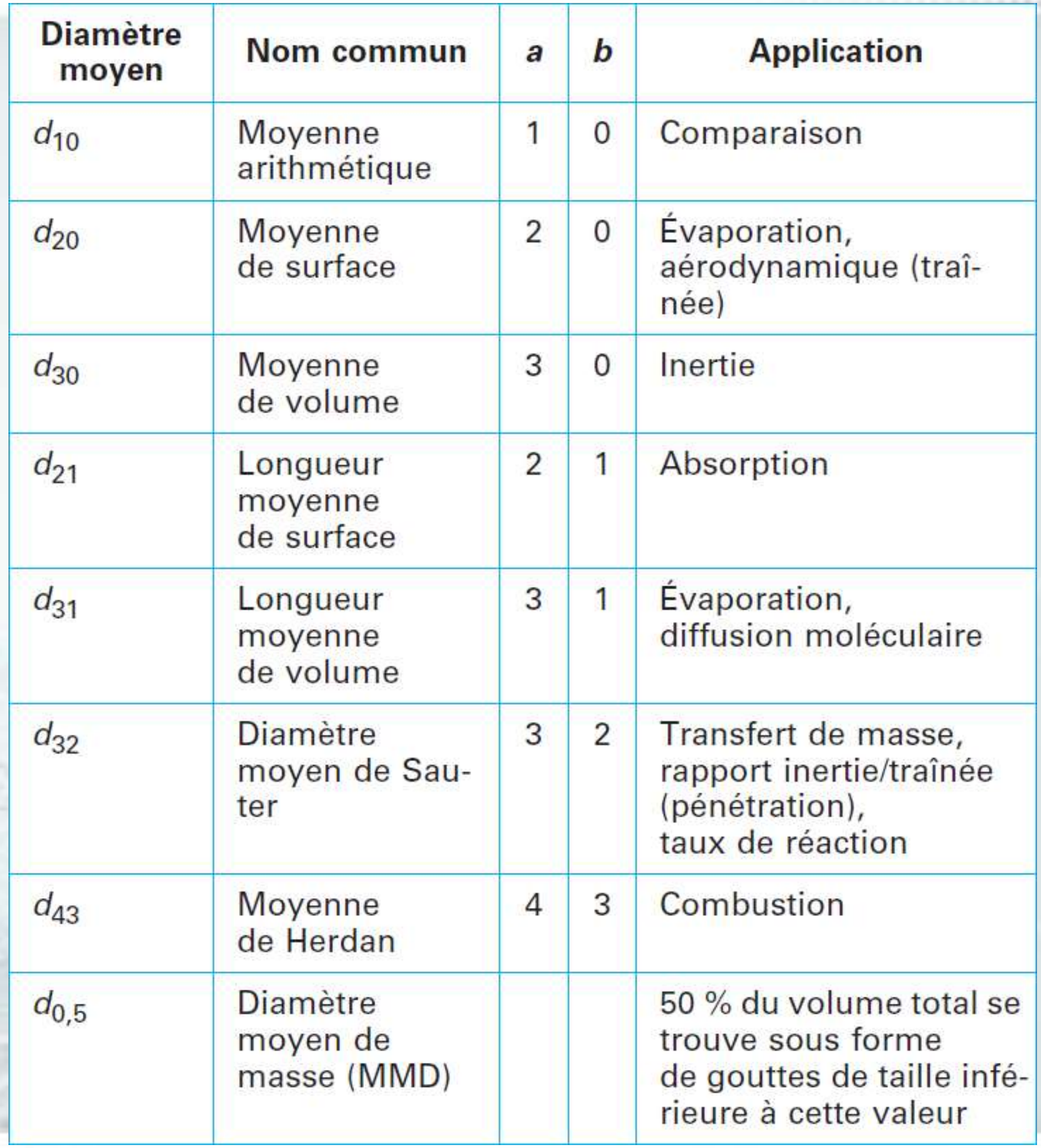
$$E = \sigma \sum_{i=1}^{i=N} \pi \, D_i^2$$

$$m_L = \rho_L \frac{\pi}{6} \sum_{i=1}^{i=N} D_i^3$$

$$E / m_L = \frac{6\sigma}{\rho_L D_{32}}$$

Caractérisation des sprays

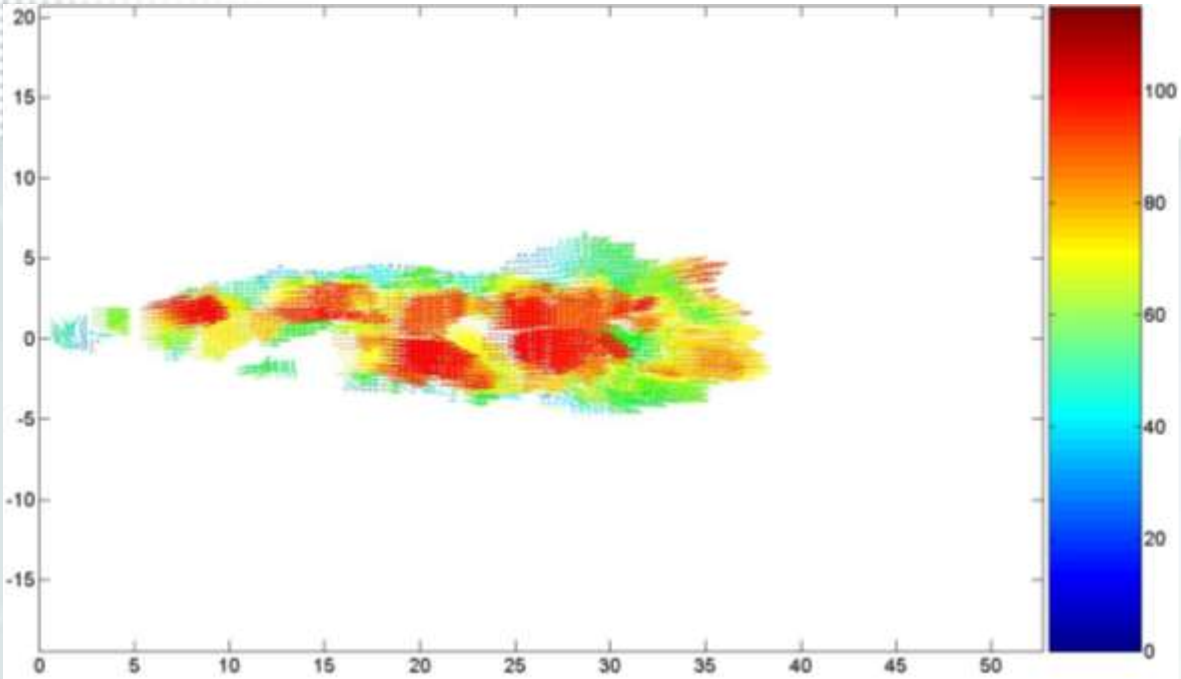
Diamètres moyens

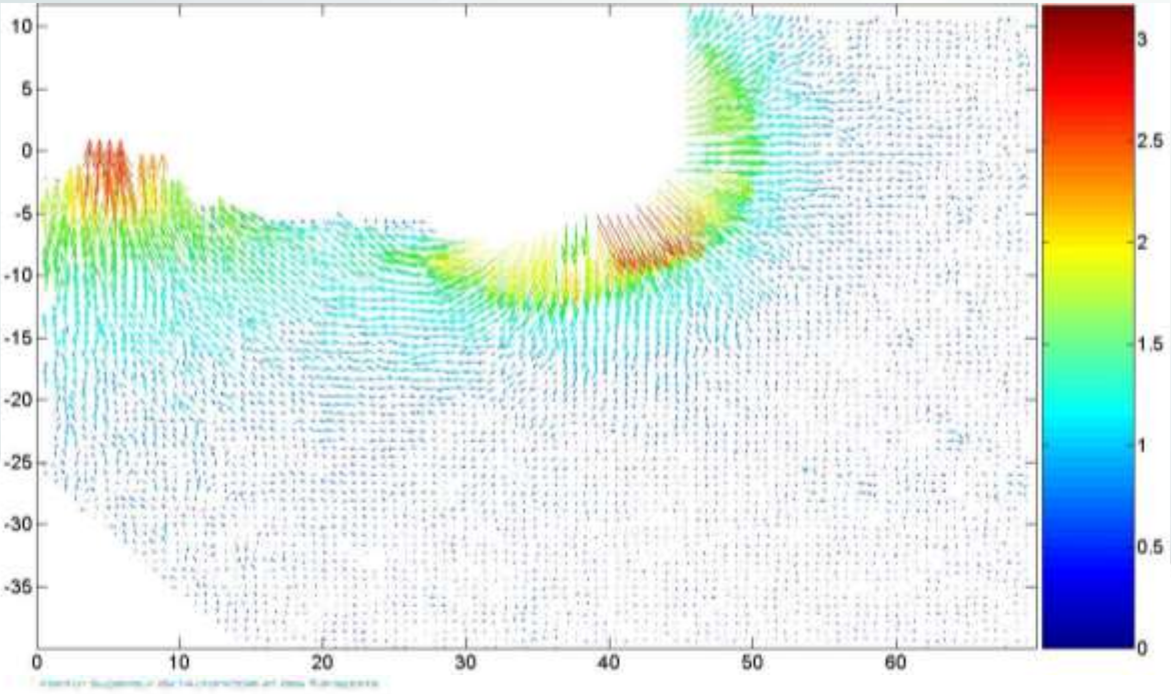


Diamètre moyen	Nom commun	*a*	*b*	Application
d_{10}	Moyenne arithmétique	1	0	Comparaison
d_{20}	Moyenne de surface	2	0	Évaporation, aérodynamique (traînée)
d_{30}	Moyenne de volume	3	0	Inertie
d_{21}	Longueur moyenne de surface	2	1	Absorption
d_{31}	Longueur moyenne de volume	3	1	Évaporation, diffusion moléculaire
d_{32}	Diamètre moyen de Sauter	3	2	Transfert de masse, rapport inertie/traînée (pénétration), taux de réaction
d_{43}	Moyenne de Herdan	4	3	Combustion
$d_{0,5}$	Diamètre moyen de masse (MMD)			50 % du volume total se trouve sous forme de gouttes de taille inférieure à cette valeur

Interactions des sprays

Air/Spray





Vitesses Spray & air

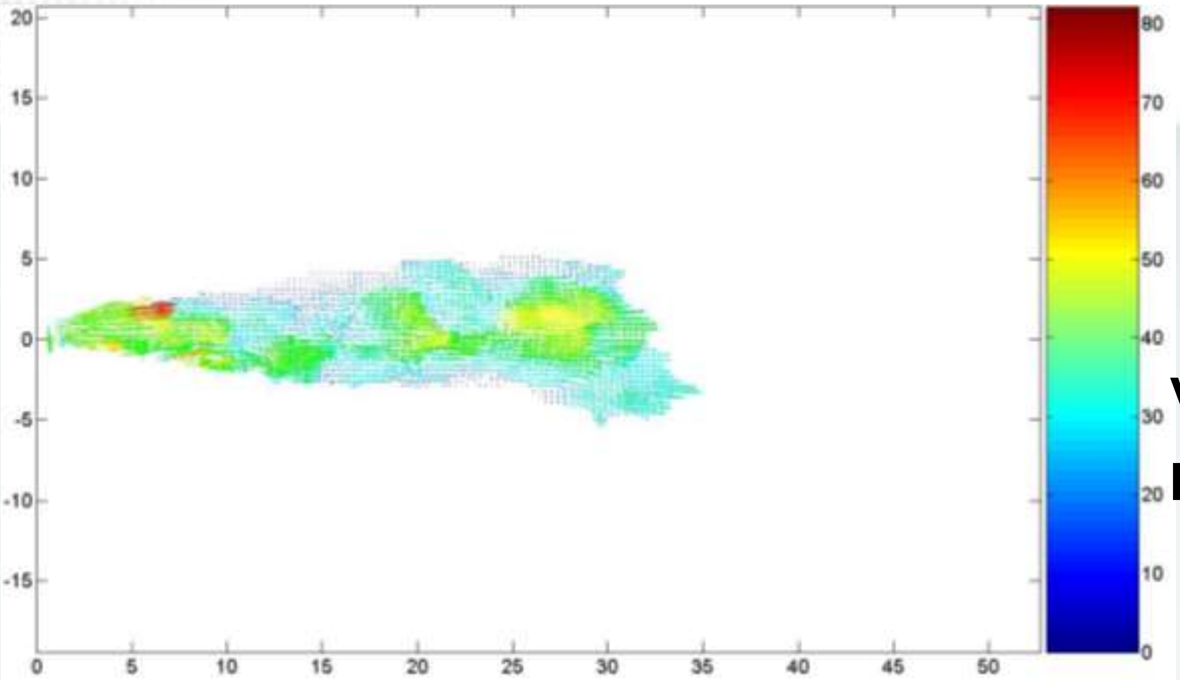
Injecteur Swirl

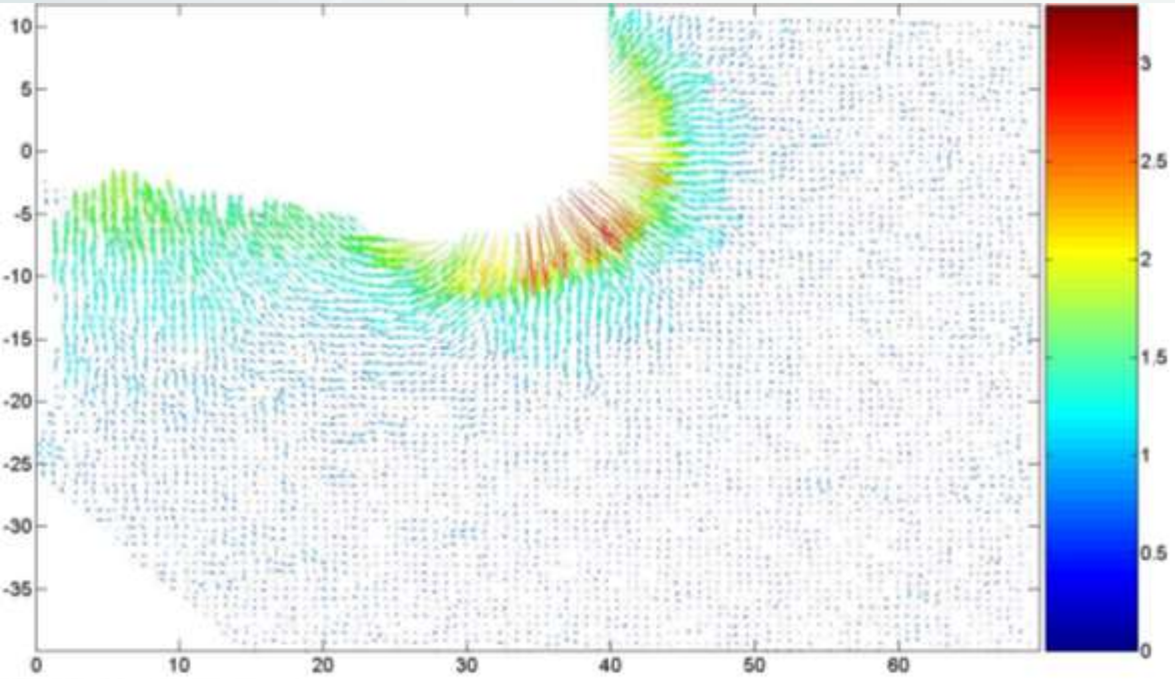
Pression Inj. 80bar

Pression atm. 5bar

500µs ASI

(mm, vitesses en m/s)





Vitesses Spray & air

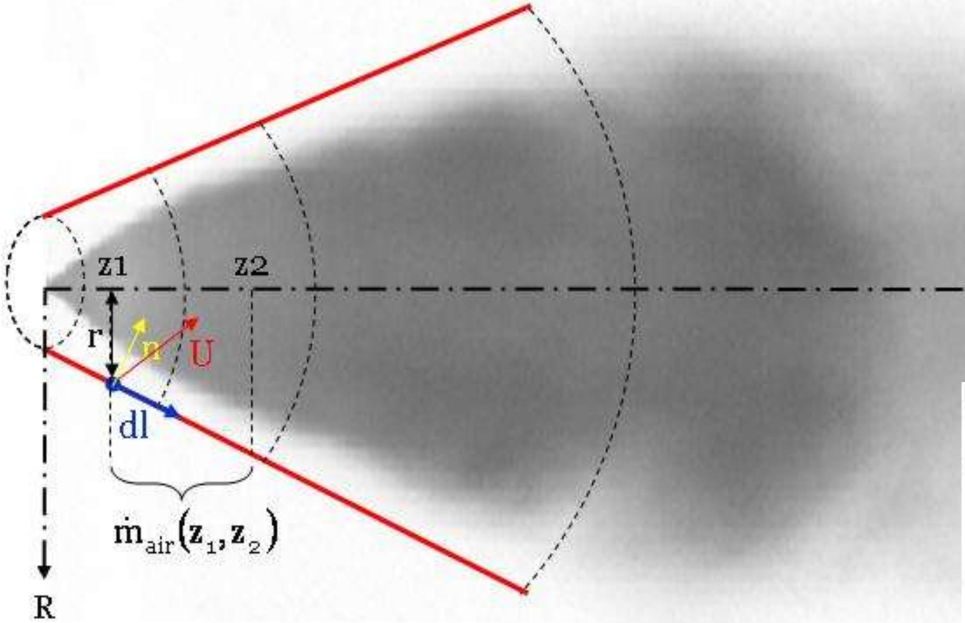
Injecteur Swirl

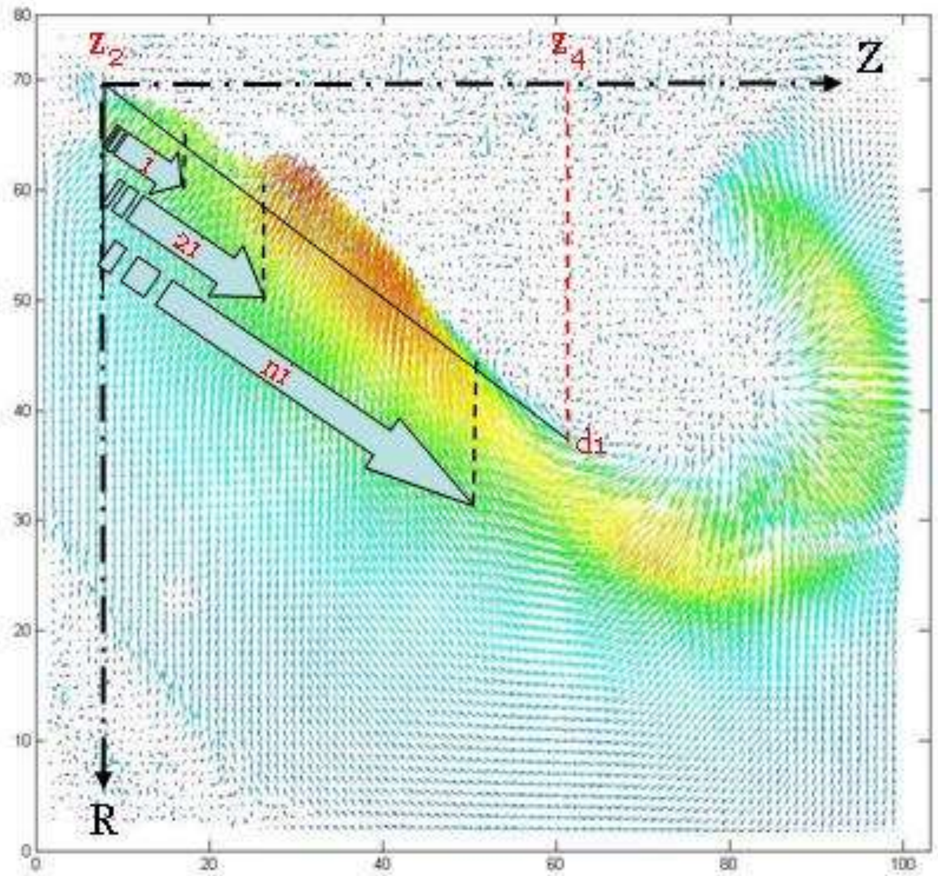
Pression Inj. 120bar

Pression atm. 10bar

500µs ASI

(mm, vitesses en m/s)





$$m_{air}(z) = \int_{z=z1}^{z=z2} \rho \cdot \overrightarrow{U}(r,z) \cdot \overrightarrow{n} \cdot 2\pi \cdot r \cdot dl$$

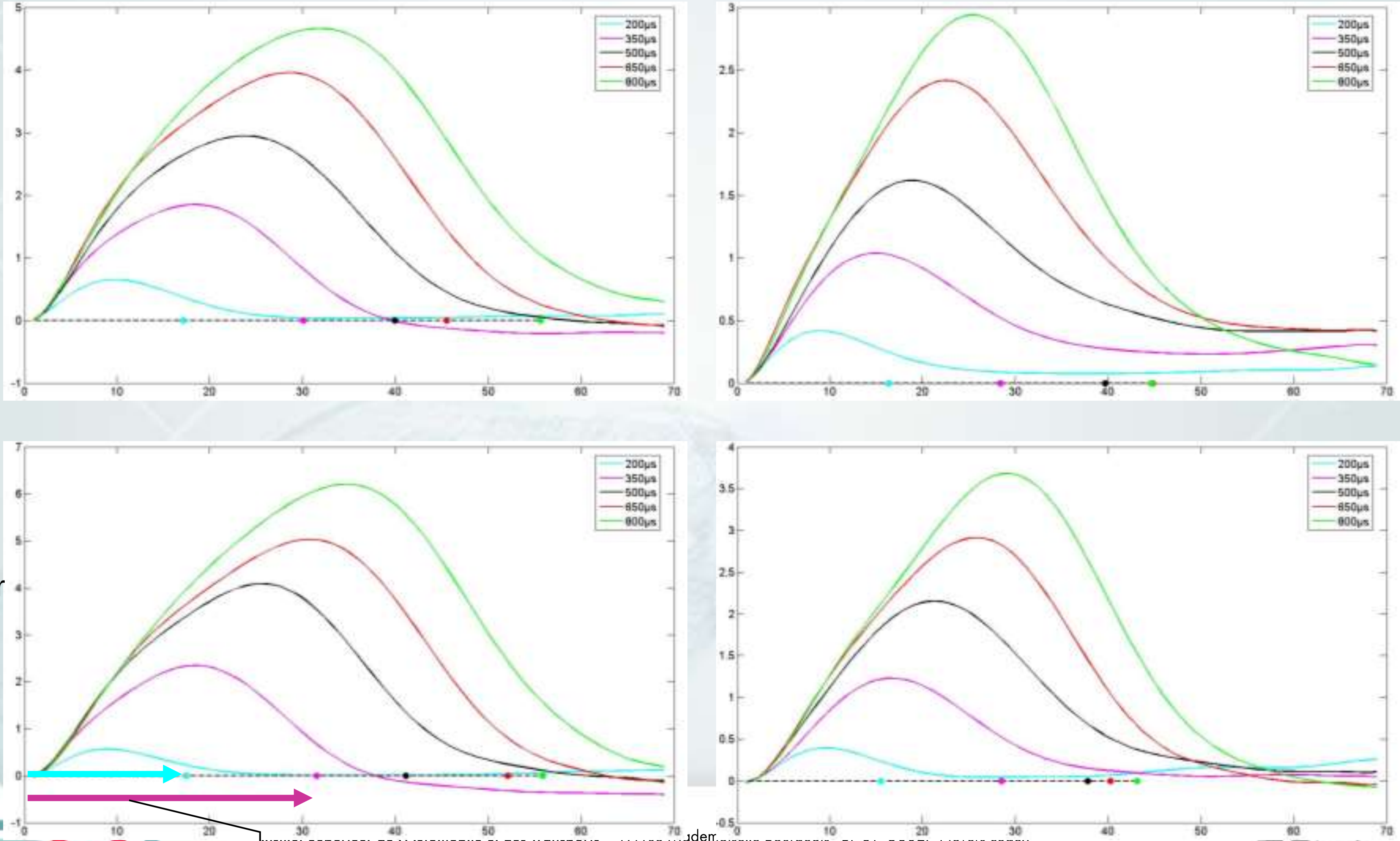
Débits air entrants dans le spray

5 bar

10 bar

80 bar

120 bar

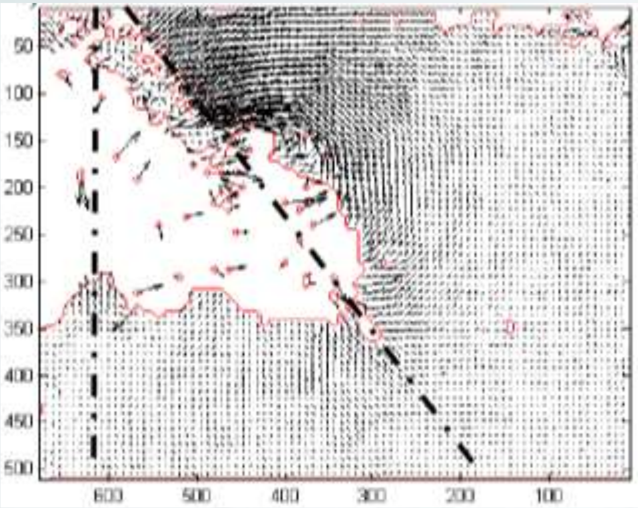


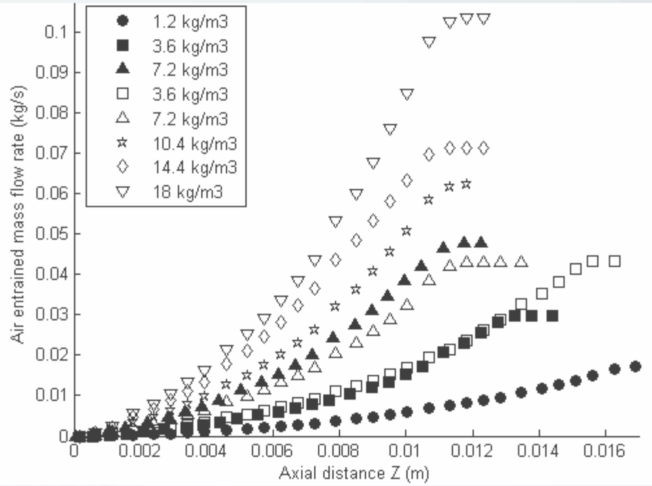
Spray tip penetration

z in mm

Interactions des sprays

Air/Spray





$$\dot{m}_e(z \to z_0) \approx \alpha_n \left(\frac{\rho_g}{\rho_0}\right)^{5/6} z(z - z_0)^{1/2}$$

$$\dot{m}_e(z >> z_0) = \alpha_f \left(\frac{\rho_g}{\rho_0}\right)^{1/2} z$$

B. Prosperi, J. Helie, R. Bazile - FPIV Study of Density Effect on Air Entrainment In Gasoline Dense Sprays 13th Int Symp on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, 26-29 June, 2006

Cossali G. E., An integral model for gas entrainment into full cone sprays. J. Fluid Mech., Vol.
439 : 353-366, 2001

Interactions des sprays

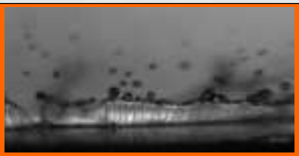
Parois/Spray

Heptane 148°c

Interactions des sprays

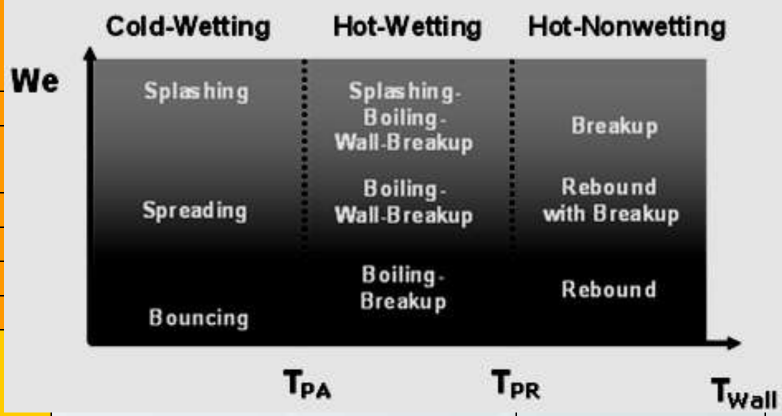
Parois/Spray

Heptane 370°c

Weber number	Wall Temperature	Heating parameter	Impingement regime	
Low (~1)	low		spreading	
	High ($T>T_{leid}$)		rebound	
high	370°C	B=2,22	Intense splash 	
			Ejection angle	45°
			Diameter distribution	
			Class 1	50% number – 5% mass
			Class 2	40 % number – 20% mass
			Class 3	10% number – 75% mass
			Class 4	none
	148°C	B=0,8	Splash 	
			Ejection angle	10°
			Diameter distribution	
			Class 1	none
			Class 2	30 % number – 0% mass
			Class 3	some
			Class 4	70 % number – 100% mass
	70°C	B=0,29	Spreading 	
			All mass deposited	

Droplet classes			
1	2	3	4
0-100 µm	100-200µm	200-450µm	450-0,9µm

Heating parameter	$B=\frac{Cp(Tw-Td)}{Lv}$
Weber impact	$We=\frac{\rho_l d v^2}{\sigma}=920$
Reynolds impact	Re=12884
Bond number	$Bo=\frac{\Delta\rho d^2 g}{4\sigma}=0.33$
Ohnesorge	$Oh=\frac{\sqrt{We}}{\mathrm{Re}}=0,00235$



Variabilité des sprays

- Fabrication
  - Perçage (laser)
  - Electro discharge machining (EDM)

- Usure – encrassement

- Instationnarité

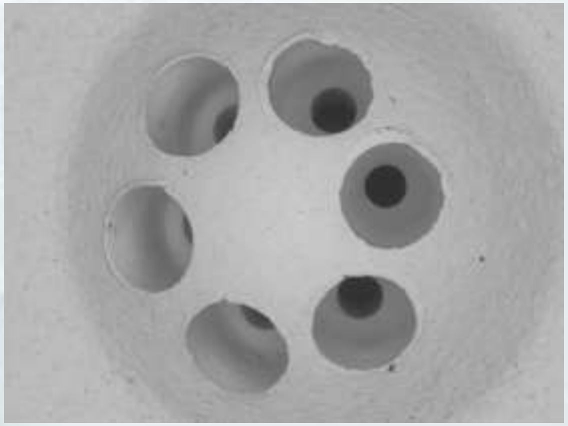
Variabilité des sprays

Fabrication

Perçage traditionnel et laser

Component milled on a DATRON M8

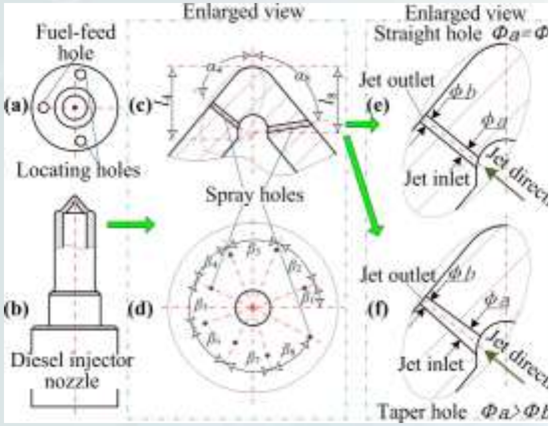
Component built into the ignition system

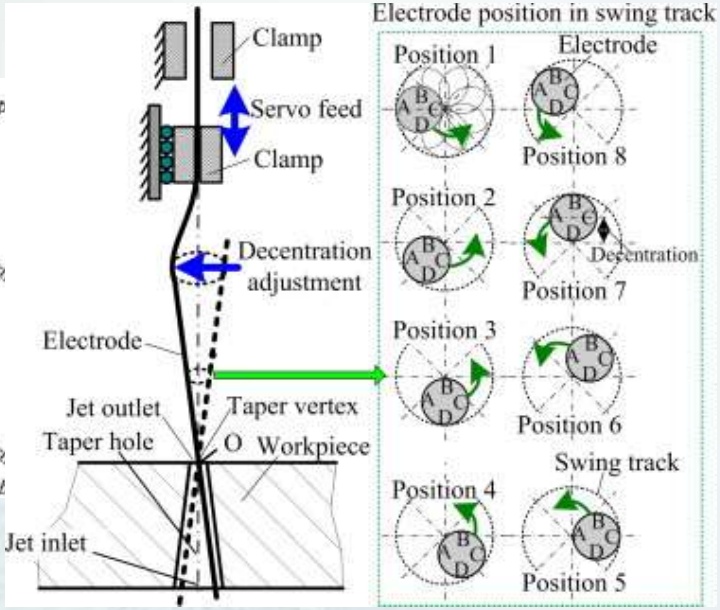


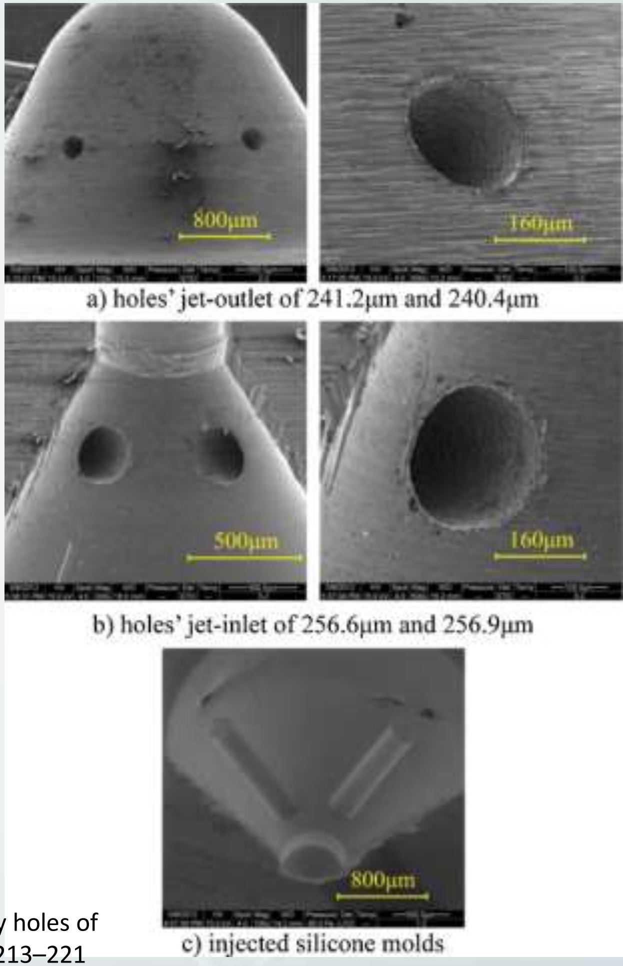
Variabilité des sprays

Fabrication

Electro discharge machining (EDM)







a) holes' jet-outlet of 241.2μm and 240.4μm

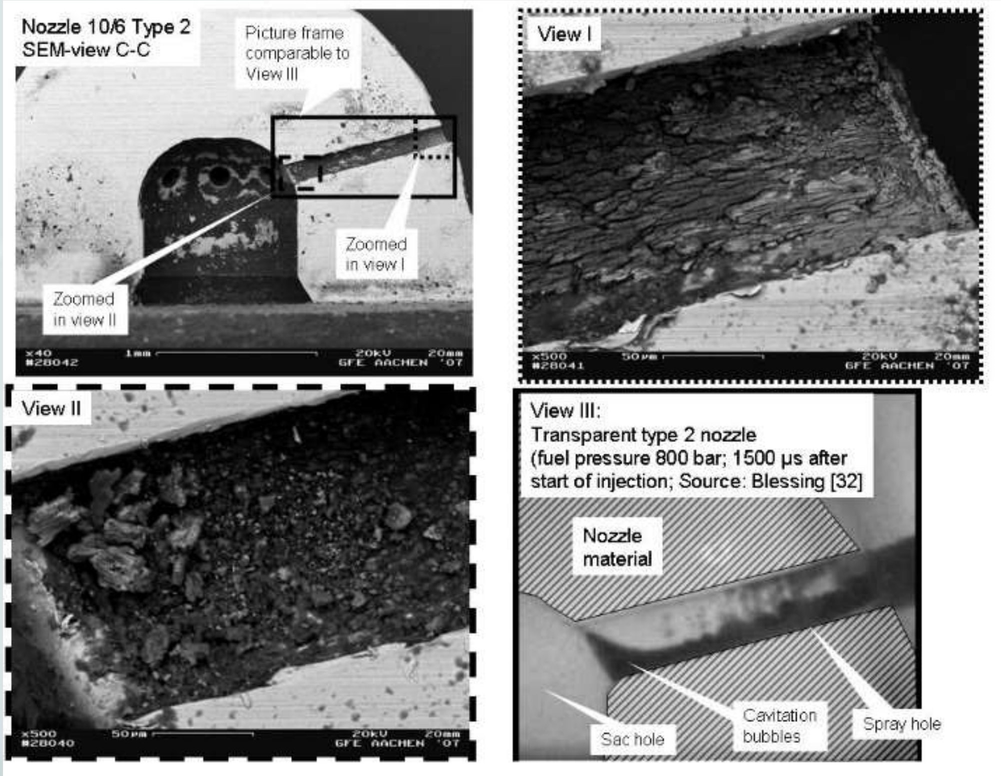
b) holes' jet-inlet of 256.6μm and 256.9μm

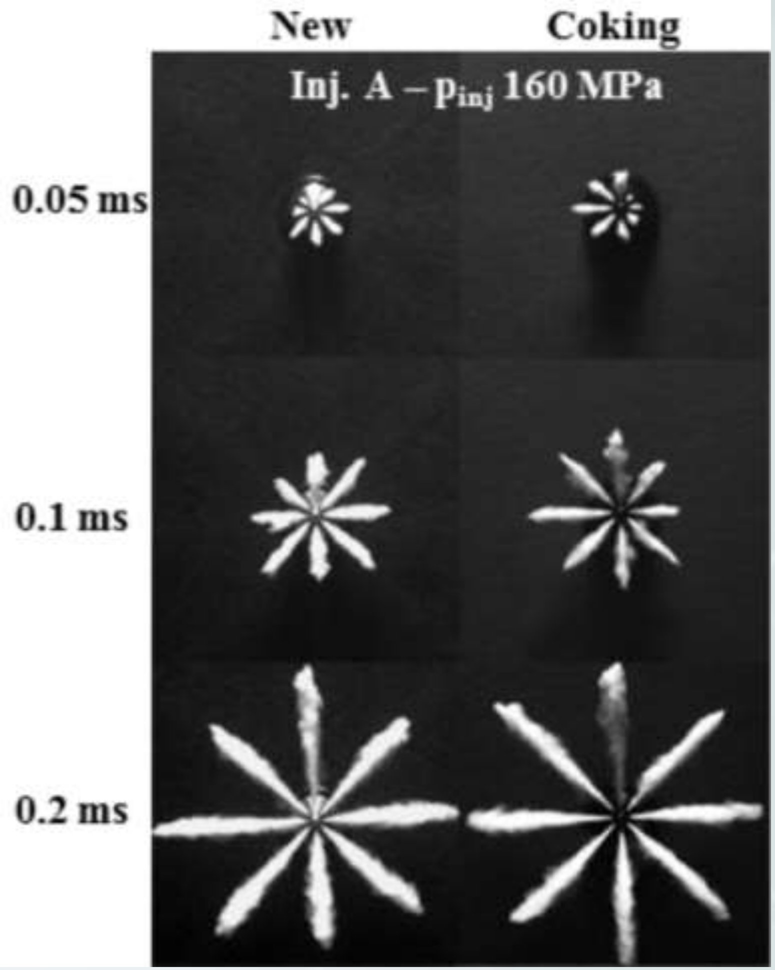
c) injected silicone molds

Hao Tonga et al., Mechanism design and process control of micro EDM for drilling spray holes of diesel injector nozzles, Precision Engineering Volume 37, Issue 1, January 2013, Pages 213–221

Variabilité des sprays

Usure – encrassement



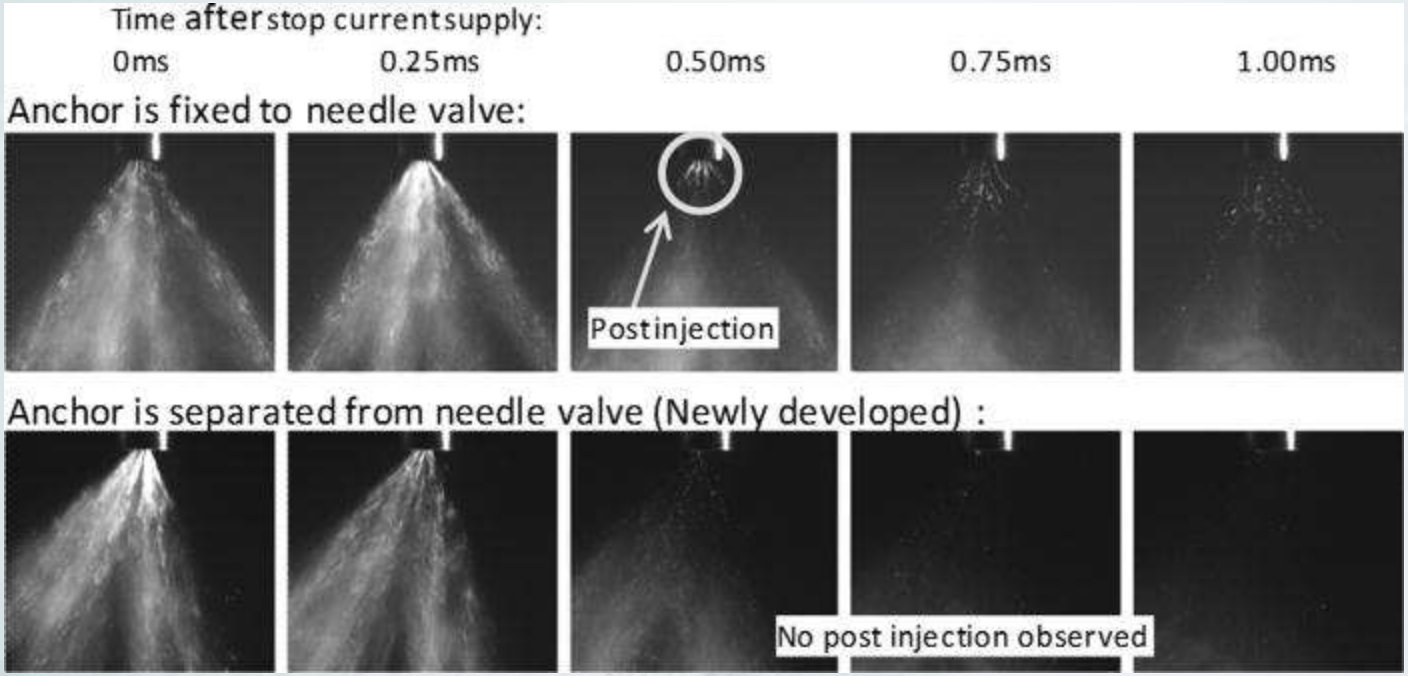


DI-Diesel Engine - Injection Nozzle Coking – FEV 2009

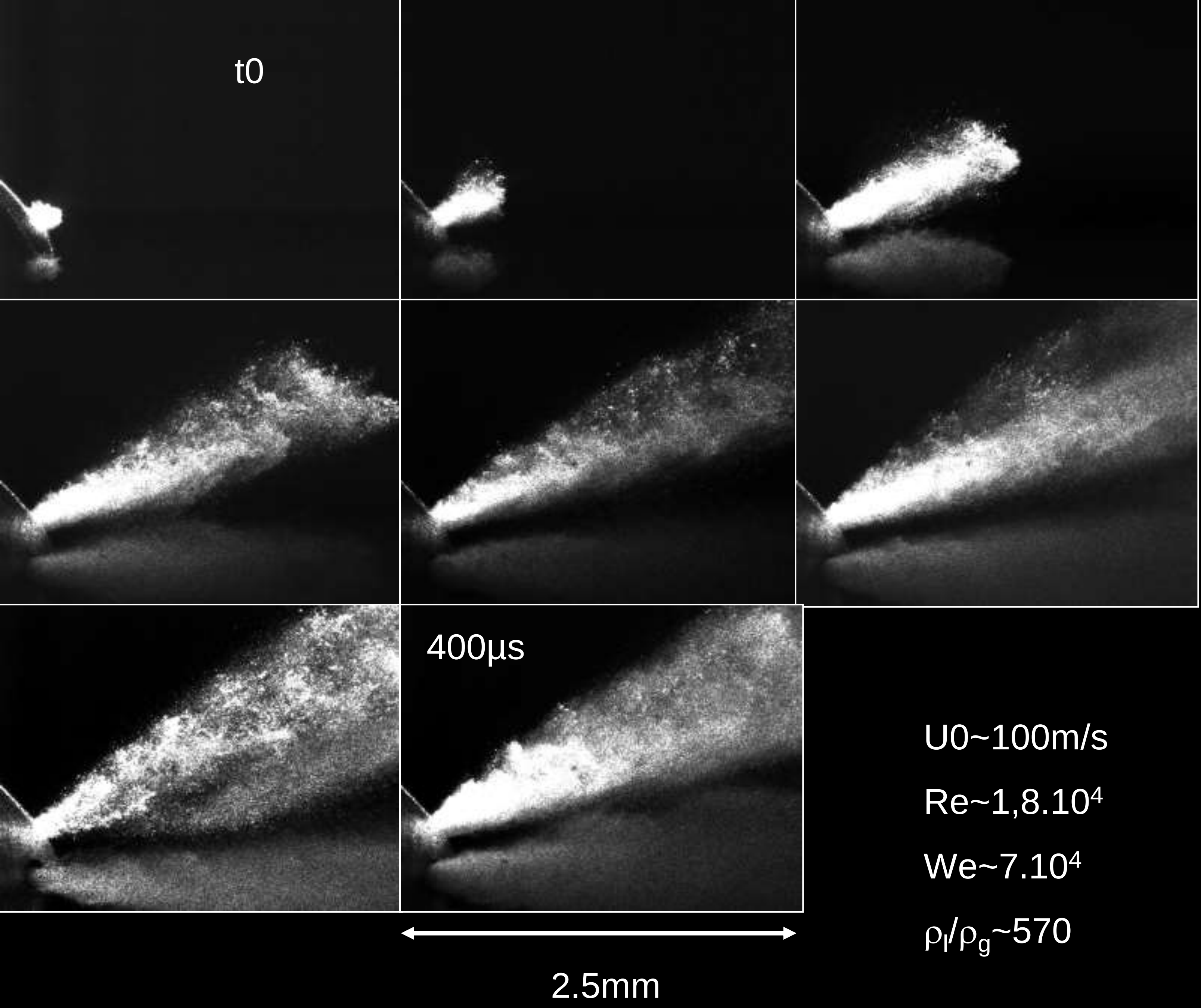
Alessandro Montanaro and Luigi Allocca, Impact of the Nozzle Coking on Spray Formation for Diesel Injectors, SAE 2013-01-2546

Variabilité des sprays

Instationnarité



Motoyuki Abe et al. - Quick Response Fuel Injector for Direct-Injection Gasoline Engines - J. Eng. Gas Turbines Power 134(6), 062803 (Apr 12, 2012)



$U0\sim100$m/s

$Re\sim1{,}8.10^4$

$We\sim7.10^4$

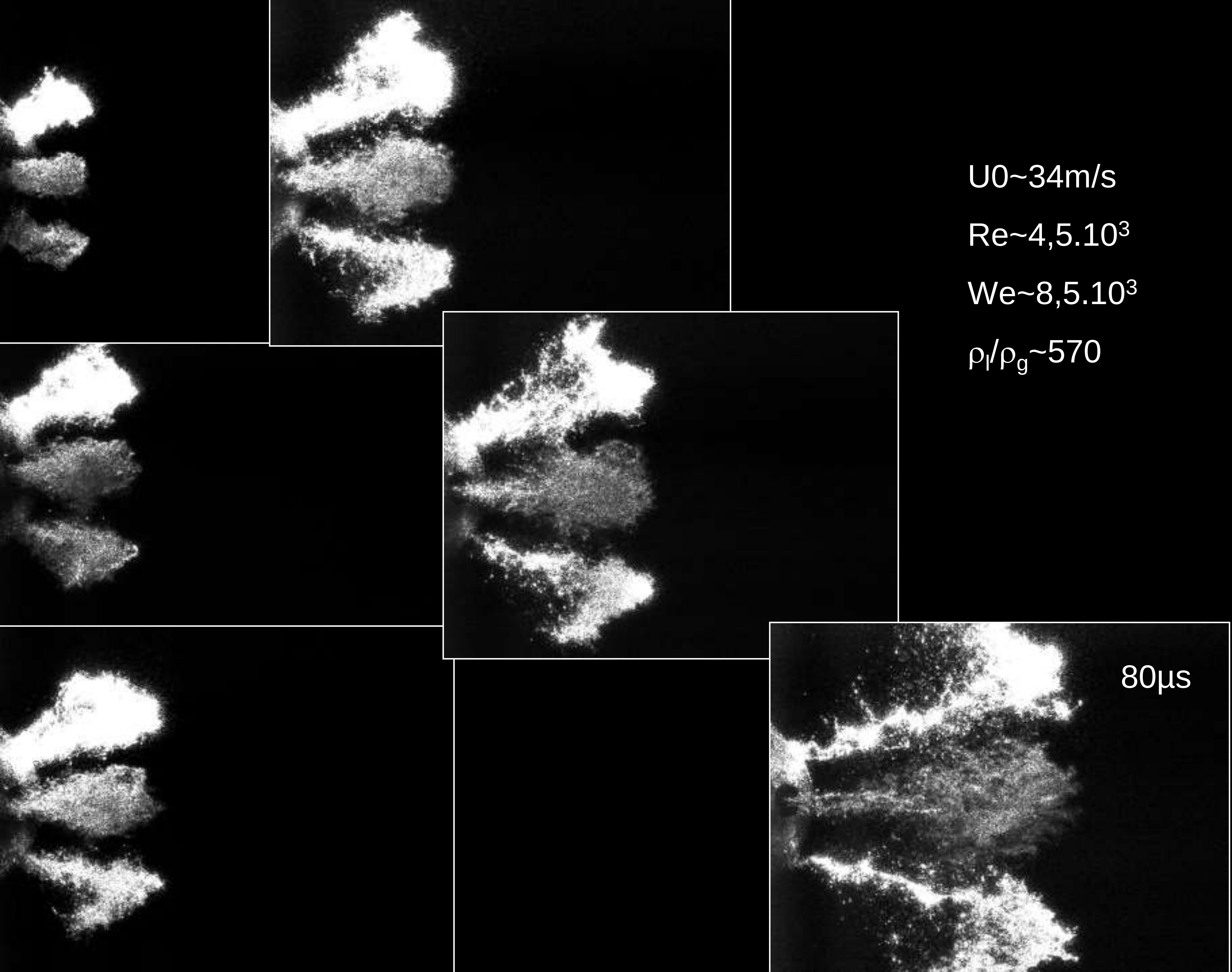
$\rho_l/\rho_g\sim570$

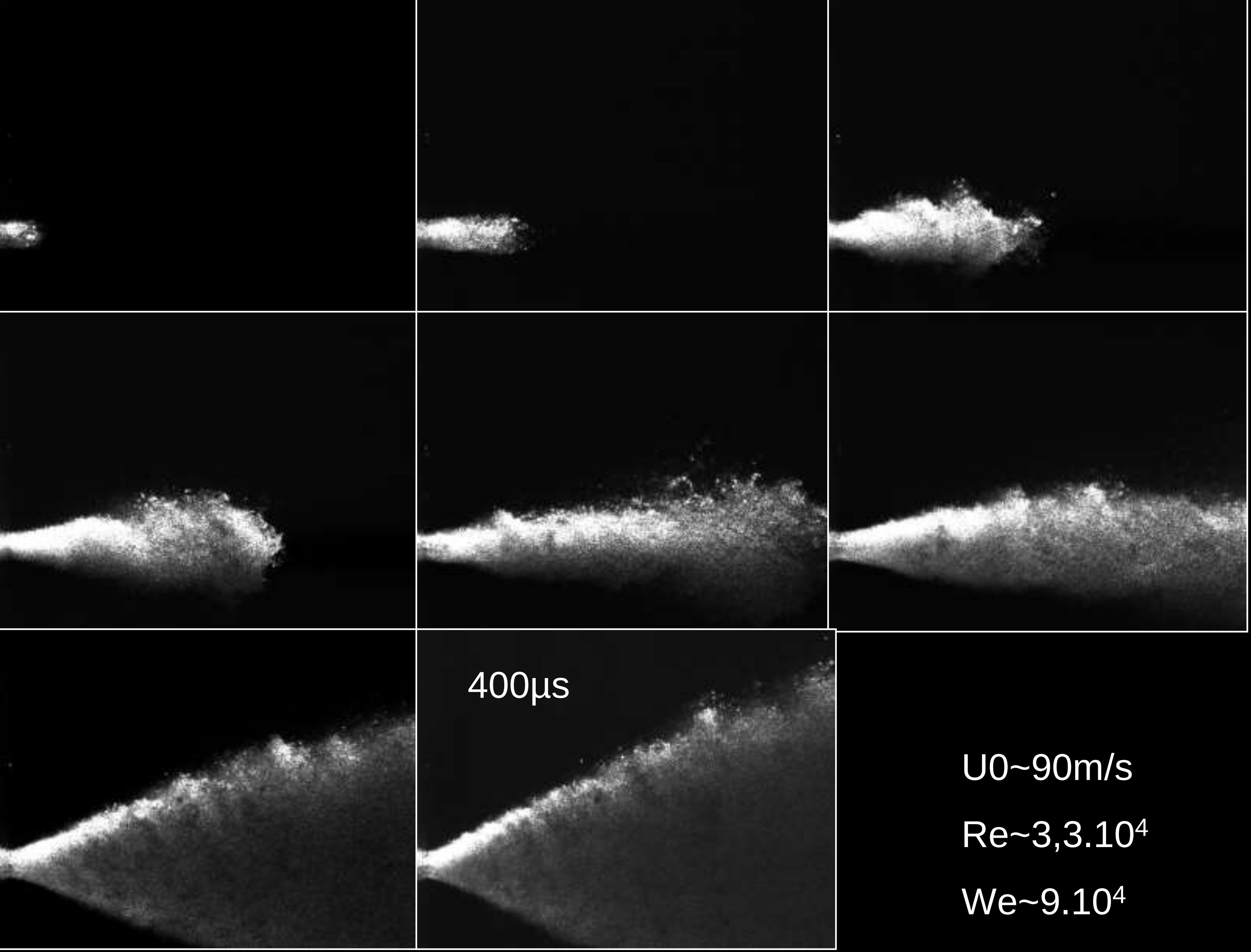
U0~34m/s

Re~$4{,}5.10^3$

We~$8{,}5.10^3$

ρ_l/ρ_g~570



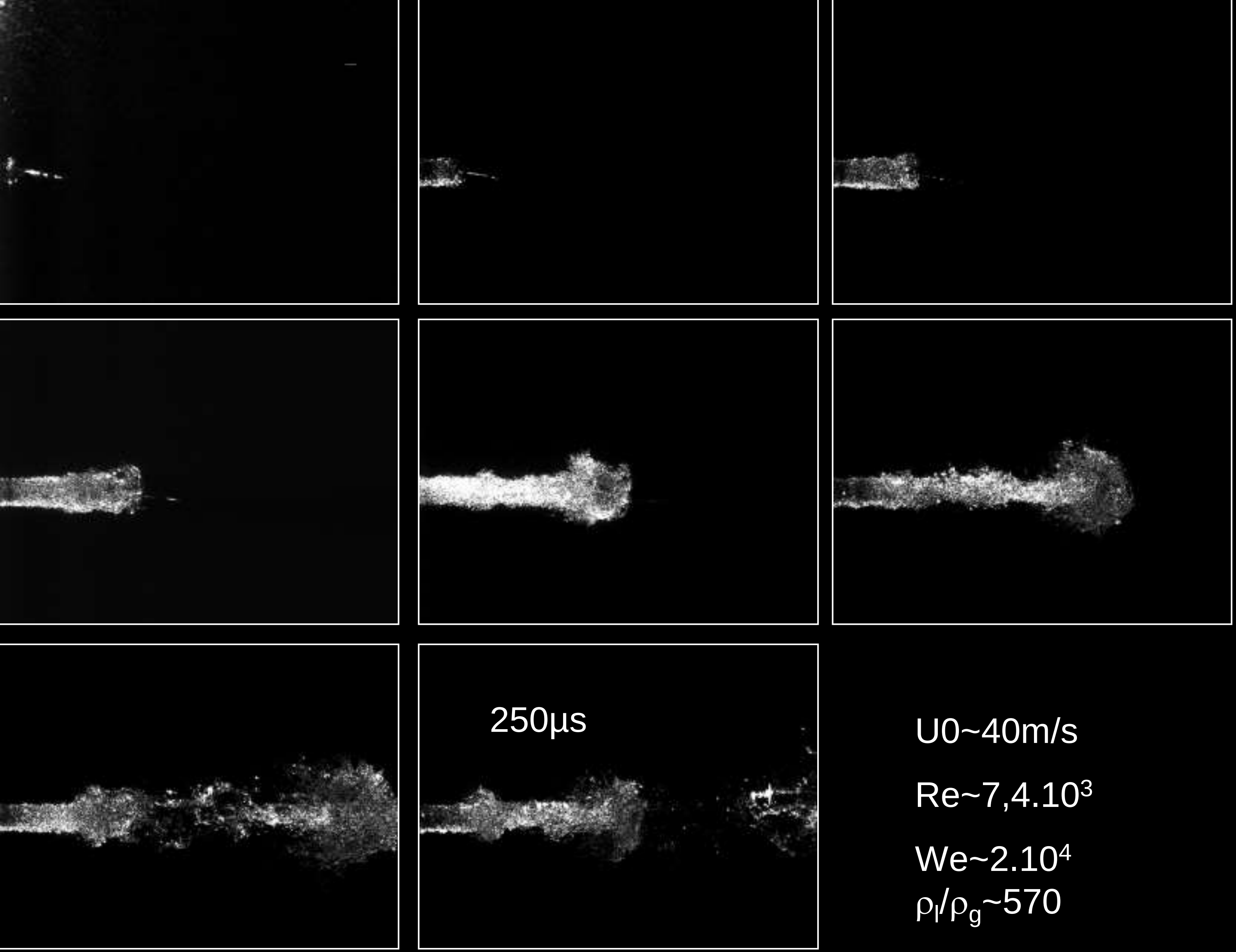


U0~90m/s

Re~3,3.10^4

We~9.10^4

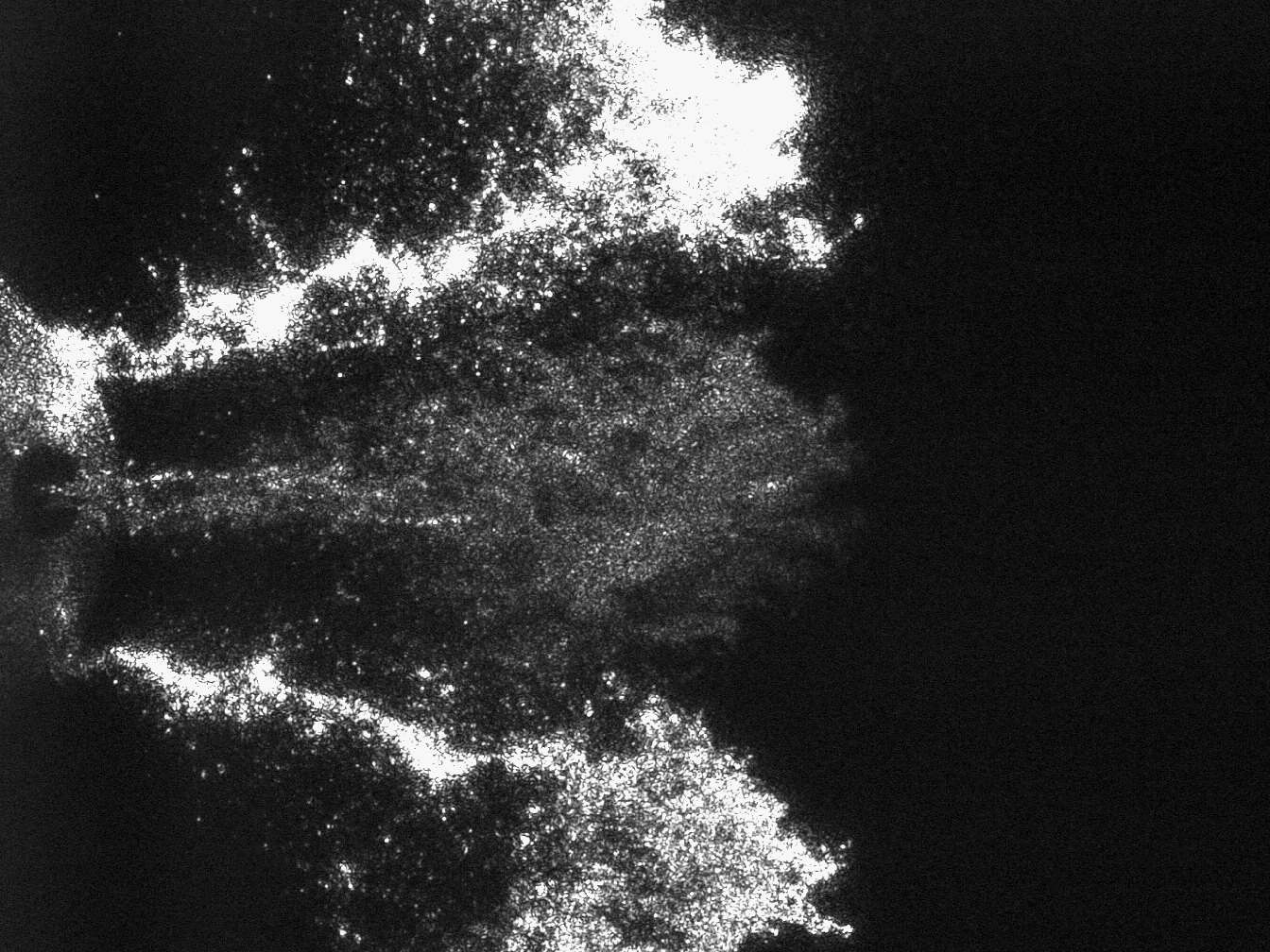
ρ_l/ρ_g~570



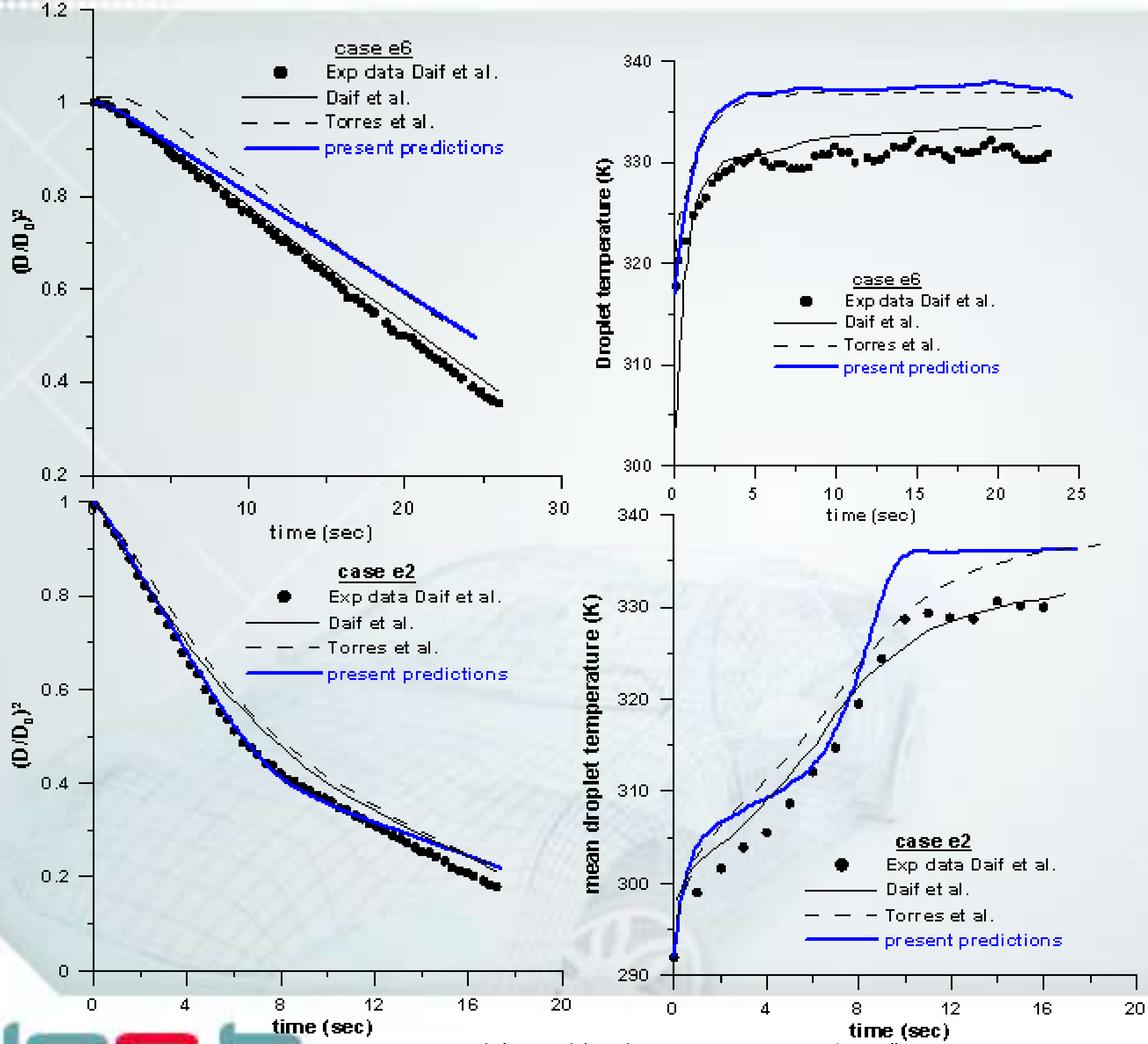
$U0 \sim 40 m/s$

$Re \sim 7,4.10^3$

$We \sim 2.10^4$
$\rho_l/\rho_g \sim 570$



Evaporation de gouttes (isolées)



Strotos, Gavaises, Theodorakakos, Bergeles, nfluence of species concentration on the evaporation of suspended multicomponent droplets, ILASS 2008

Modélisation

Problème d’échelle

Gouttes ~ 10^{-6}m

Chambre ~ 10^{-1}m

Modélisation

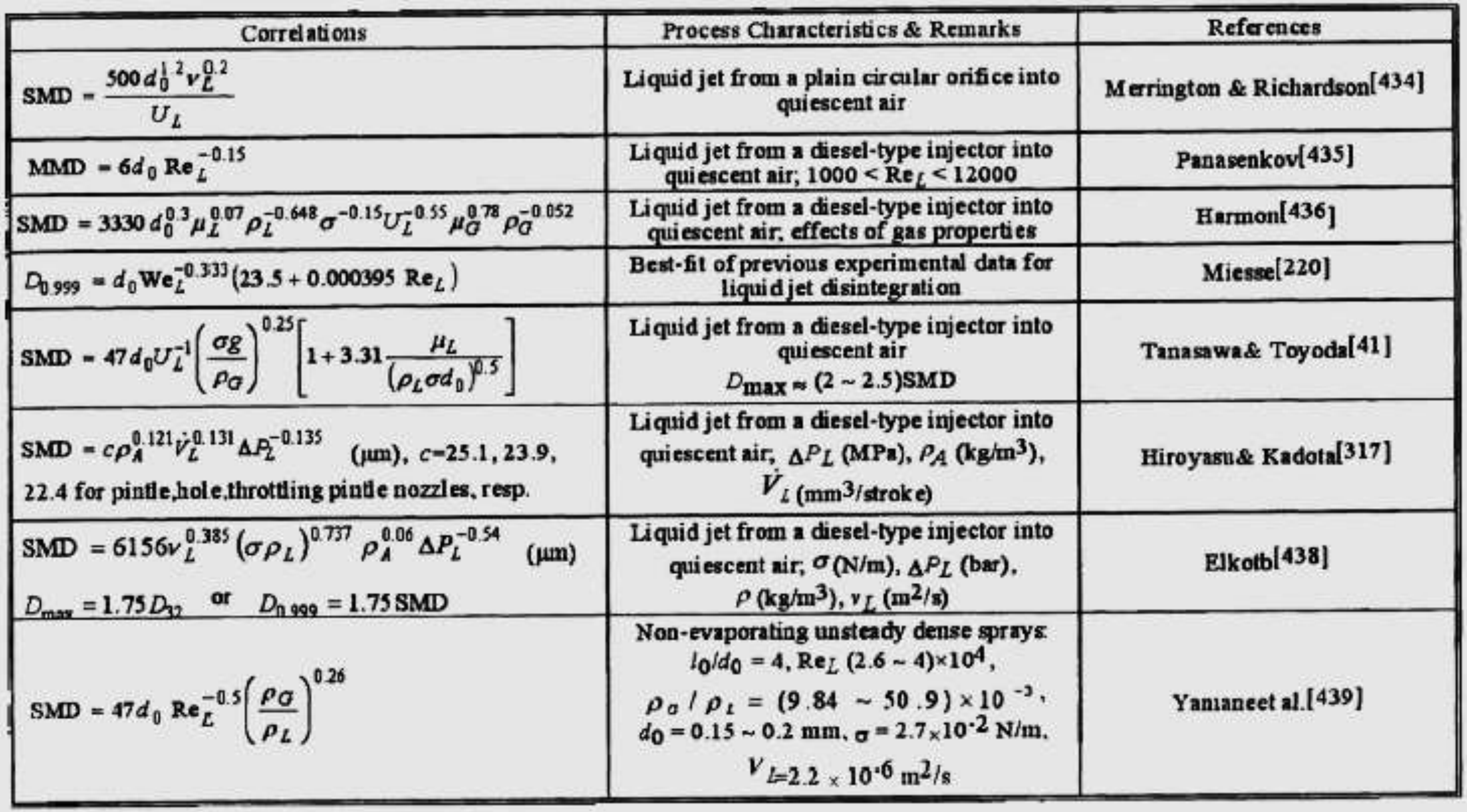
F Dos Santos, L Le Moyne (2011) Spray Atomization Models in Engine Applications, from Correlations to Direct Numerical Simulations Oil & Gas Science and Technology , Vol. 66 (2011), No. 5, pp. 801-822

Principes

- Corrélations
  - Taille, angle, pénétration
- Modèles « mécanistiques »
  - Cavitation, instabilités, elsa, TAB, etc.
- Modèles « statistiques »
  - Cascades de rupture, PBE, etc.

Modèle ≠ Simulation numérique

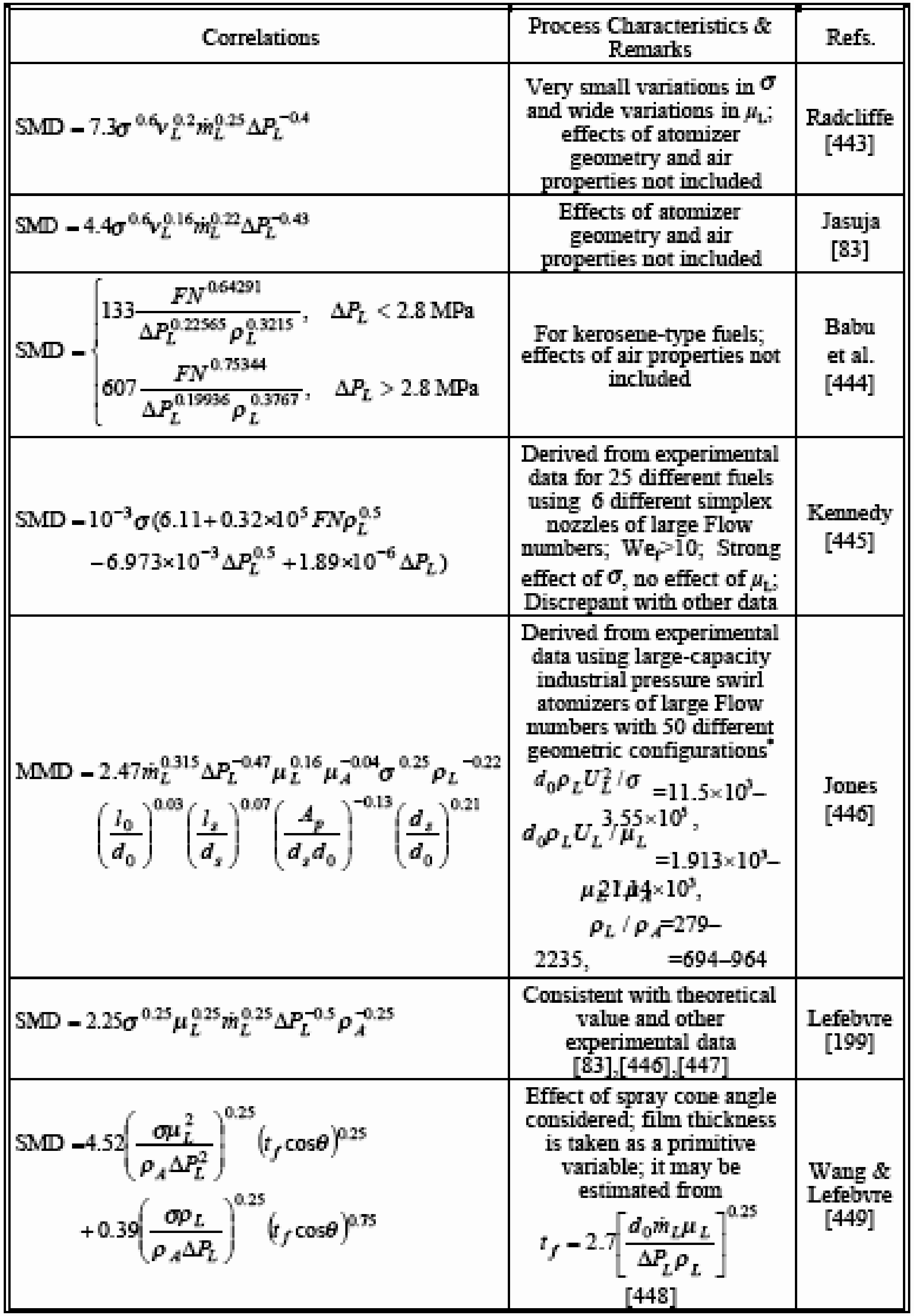
Corrélations – Rupture de jet



Correlations	Process Characteristics & Remarks	References
$\mathrm{SMD} = \dfrac{500 d_0^{1.2} \nu_L^{0.2}}{U_L}$	Liquid jet from a plain circular orifice into quiescent air	Merrington & Richardson[434]
$\mathrm{MMD} = 6 d_0 \,\mathrm{Re}_L^{-0.15}$	Liquid jet from a diesel-type injector into quiescent air; $1000 < \mathrm{Re}_L < 12000$	Panasenkov[435]
$\mathrm{SMD} = 3330\, d_0^{0.3} \mu_L^{0.07} \rho_L^{-0.648} \sigma^{-0.15} U_L^{-0.55} \mu_G^{0.78} \rho_G^{-0.052}$	Liquid jet from a diesel-type injector into quiescent air; effects of gas properties	Harmon[436]
$D_{0.999} = d_0 \mathrm{We}_L^{-0.333} (23.5 + 0.000395\, \mathrm{Re}_L)$	Best-fit of previous experimental data for liquid jet disintegration	Miesse[220]
$\mathrm{SMD} = 47 d_0 U_L^{-1} \left(\dfrac{\sigma g}{\rho_G}\right)^{0.25} \left[1 + 3.31 \dfrac{\mu_L}{(\rho_L \sigma d_0)^{0.5}}\right]$	Liquid jet from a diesel-type injector into quiescent air $D_{\max} \approx (2 \sim 2.5)\mathrm{SMD}$	Tanasawa & Toyoda[41]
$\mathrm{SMD} = c \rho_A^{0.121} \dot{V}_L^{0.131} \Delta P_L^{-0.135}$ (µm), c=25.1, 23.9, 22.4 for pintle, hole, throttling pintle nozzles, resp.	Liquid jet from a diesel-type injector into quiescent air; ΔP_L (MPa), ρ_A (kg/m^3), $\dot{V}_L$ (mm^3/stroke)	Hiroyasu & Kadota[317]
$\mathrm{SMD} = 6156 \nu_L^{0.385} (\sigma \rho_L)^{0.737} \rho_A^{0.06} \Delta P_L^{-0.54}$ (µm) $D_{\max} = 1.75 D_{32}$ or $D_{0.999} = 1.75\,\mathrm{SMD}$	Liquid jet from a diesel-type injector into quiescent air; σ (N/m), ΔP_L (bar), ρ (kg/m^3), ν_L (m^2/s)	Elkotb[438]
$\mathrm{SMD} = 47 d_0 \,\mathrm{Re}_L^{-0.5} \left(\dfrac{\rho_G}{\rho_L}\right)^{0.26}$	Non-evaporating unsteady dense sprays: $l_0/d_0 = 4$, Re_L $(2.6 \sim 4)\times 10^4$, $\rho_G / \rho_L = (9.84 \sim 50.9)\times 10^{-3}$, $d_0 = 0.15 \sim 0.2$ mm, $\sigma = 2.7\times 10^{-2}$ N/m, $\nu_L = 2.2 \times 10^{-6}$ m^2/s	Yamane et al.[439]

Modélisation

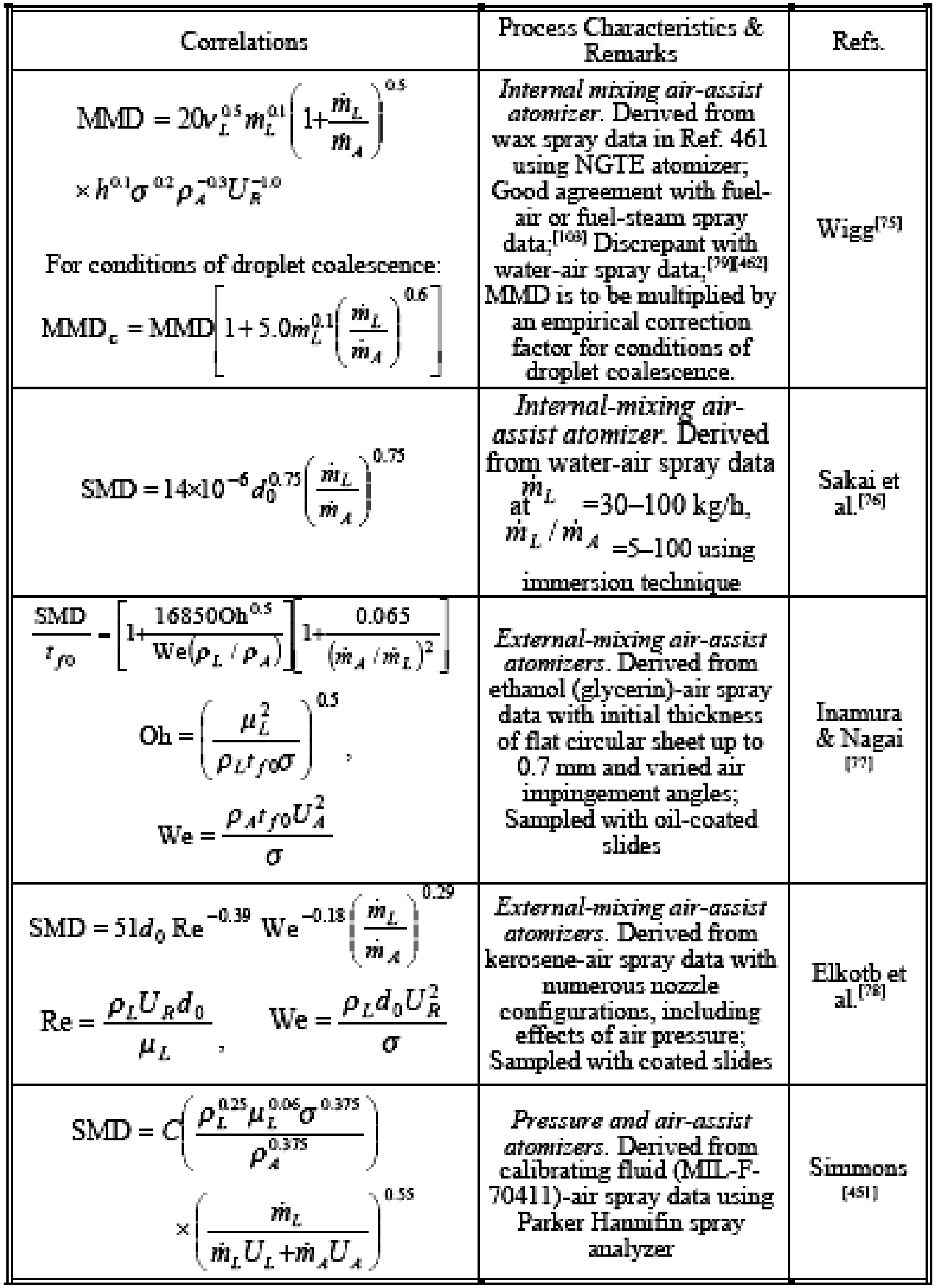
Corrélations – Rupture de cône



Correlations	Process Characteristics & Remarks	Refs.
$SMD = 7.3\sigma^{0.6}\nu_L^{0.2}\dot{m}_L^{0.25}\Delta P_L^{-0.4}$	Very small variations in σ and wide variations in μ_L; effects of atomizer geometry and air properties not included	Radcliffe [443]
$SMD = 4.4\sigma^{0.6}\nu_L^{0.16}\dot{m}_L^{0.22}\Delta P_L^{-0.43}$	Effects of atomizer geometry and air properties not included	Jasuja [83]
$SMD = \begin{cases} 133\dfrac{FN^{0.64291}}{\Delta P_L^{0.22565}\rho_L^{0.3215}}, & \Delta P_L < 2.8\text{ MPa} \\ 607\dfrac{FN^{0.75344}}{\Delta P_L^{0.19936}\rho_L^{0.3767}}, & \Delta P_L > 2.8\text{ MPa} \end{cases}$	For kerosene-type fuels; effects of air properties not included	Babu et al. [444]
$SMD = 10^{-3}\sigma(6.11+0.32\times10^{5}FN\rho_L^{0.5} -6.973\times10^{-3}\Delta P_L^{0.5}+1.89\times10^{-6}\Delta P_L)$	Derived from experimental data for 25 different fuels using 6 different simplex nozzles of large Flow numbers; $We_f>10$; Strong effect of σ, no effect of μ_L; Discrepant with other data	Kennedy [445]
$MMD = 2.47\dot{m}_L^{0.315}\Delta P_L^{-0.47}\mu_L^{0.16}\mu_A^{-0.04}\sigma^{0.25}\rho_L^{-0.22}\left(\dfrac{l_0}{d_0}\right)^{0.03}\left(\dfrac{l_s}{d_s}\right)^{0.07}\left(\dfrac{A_p}{d_s d_0}\right)^{-0.13}\left(\dfrac{d_s}{d_0}\right)^{0.21}$	Derived from experimental data using large-capacity industrial pressure swirl atomizers of large Flow numbers with 50 different geometric configurations* $d_0\rho_L U_L^2/\sigma$ =11.5×10³–3.55×10³, $d_0\rho_L U_L/\mu_L$ =1.913×10³–21.14×10³, ρ_L/ρ_A=279–2235, μ_L/μ_A =694–964	Jones [446]
$SMD = 2.25\sigma^{0.25}\mu_L^{0.25}\dot{m}_L^{0.25}\Delta P_L^{-0.5}\rho_A^{-0.25}$	Consistent with theoretical value and other experimental data [83],[446],[447]	Lefebvre [199]
$SMD = 4.52\left(\dfrac{\sigma\mu_L^2}{\rho_A\Delta P_L^2}\right)^{0.25}(t_f\cos\theta)^{0.25}+0.39\left(\dfrac{\sigma\rho_L}{\rho_A\Delta P_L}\right)^{0.25}(t_f\cos\theta)^{0.75}$	Effect of spray cone angle considered; film thickness is taken as a primitive variable; it may be estimated from $t_f = 2.7\left[\dfrac{d_0\dot{m}_L\mu_L}{\Delta P_L\rho_L}\right]^{0.25}$ [448]	Wang & Lefebvre [449]

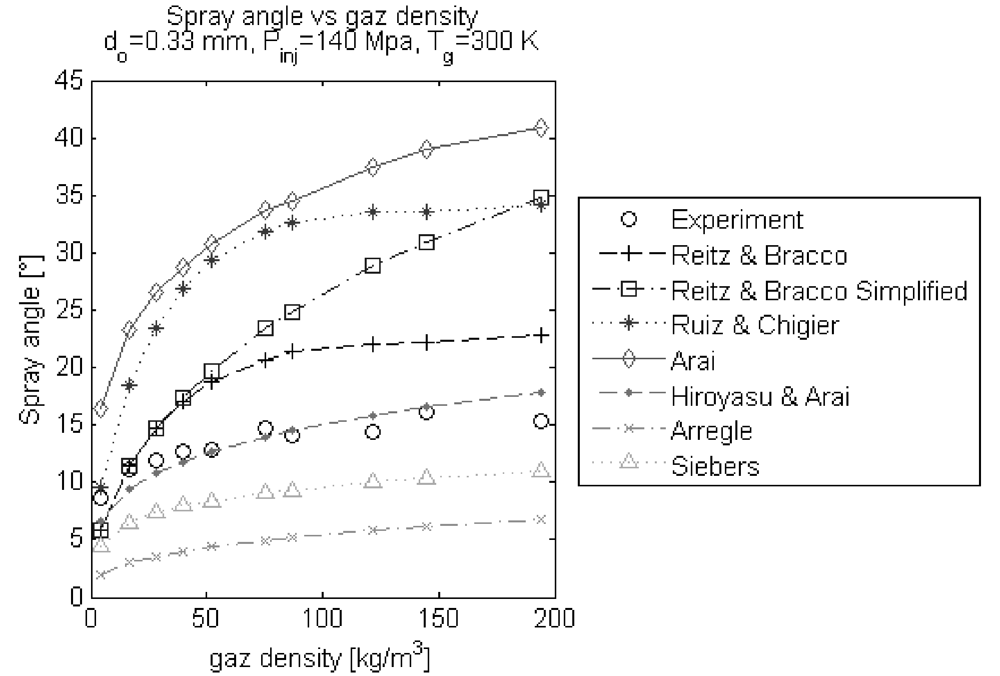
Modélisation

Corrélations – Assistance air



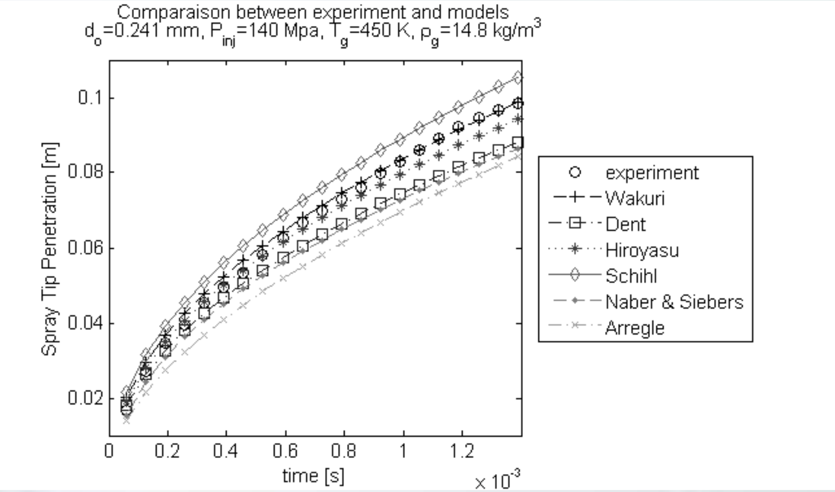
Correlations	Process Characteristics & Remarks	Refs.
$\mathrm{MMD} = 20 v_L^{0.5} \dot{m}_L^{0.1} \left(1+\frac{\dot{m}_L}{\dot{m}_A}\right)^{0.5}$ $\times h^{0.1} \sigma^{0.2} \rho_A^{-0.3} U_R^{-1.0}$ For conditions of droplet coalescence: $\mathrm{MMD}_c = \mathrm{MMD}\left[1+5.0 \dot{m}_L^{0.1} \left(\frac{\dot{m}_L}{\dot{m}_A}\right)^{0.6}\right]$	*Internal mixing air-assist atomizer*. Derived from wax spray data in Ref. 461 using NGTE atomizer; Good agreement with fuel-air or fuel-steam spray data;[108] Discrepant with water-air spray data;[79][462] MMD is to be multiplied by an empirical correction factor for conditions of droplet coalescence.	Wigg[75]
$\mathrm{SMD} = 14\times10^{-6} d_0^{0.75} \left(\frac{\dot{m}_L}{\dot{m}_A}\right)^{0.75}$	*Internal-mixing air-assist atomizer*. Derived from water-air spray data at $\dot{m}_L$ =30–100 kg/h, $\dot{m}_L / \dot{m}_A$ =5–100 using immersion technique	Sakai et al.[76]
$\frac{\mathrm{SMD}}{t_{f0}} - \left[1+\frac{16850\,\mathrm{Oh}^{0.5}}{\mathrm{We}(\rho_L / \rho_A)}\right]\left[1+\frac{0.065}{(\dot{m}_A / \dot{m}_L)^2}\right]$ $\mathrm{Oh} = \left(\frac{\mu_L^2}{\rho_L t_{f0} \sigma}\right)^{0.5},$ $\mathrm{We} = \frac{\rho_A t_{f0} U_A^2}{\sigma}$	*External-mixing air-assist atomizers*. Derived from ethanol (glycerin)-air spray data with initial thickness of flat circular sheet up to 0.7 mm and varied air impingement angles; Sampled with oil-coated slides	Inamura & Nagai [77]
$\mathrm{SMD} = 51 d_0 \,\mathrm{Re}^{-0.39}\, \mathrm{We}^{-0.18} \left(\frac{\dot{m}_L}{\dot{m}_A}\right)^{0.29}$ $\mathrm{Re} = \frac{\rho_L U_R d_0}{\mu_L}, \quad \mathrm{We} = \frac{\rho_L d_0 U_R^2}{\sigma}$	*External-mixing air-assist atomizers*. Derived from kerosene-air spray data with numerous nozzle configurations, including effects of air pressure; Sampled with coated slides	Elkotb et al.[78]
$\mathrm{SMD} = C\left(\frac{\rho_L^{0.25} \mu_L^{0.06} \sigma^{0.375}}{\rho_A^{0.375}}\right)$ $\times \left(\frac{\dot{m}_L}{\dot{m}_L U_L + \dot{m}_A U_A}\right)^{0.55}$	*Pressure and air-assist atomizers*. Derived from calibrating fluid (MIL-F-70411)-air spray data using Parker Hannifin spray analyzer	Simmons [451]

Corrélations - angle



Corrélations - pénétration

Model	Correlation	Reference
Wakuri	[illegible]	(Wakuri et al. 1960)
Dent	[illegible]	(Dent 1971)
Hiroyasu	[illegible]	(Hiroyasu & Arai 1990)
Schihl	[illegible]	(Schihl et al. 1996)
Naber & Siebers	$\tilde{S}=\left[\left(\frac{1}{\tilde{t}}\right)^{n}+\left(\frac{1}{\tilde{t}^{0.5}}\right)^{n}\right]^{-\frac{1}{n}}$	(Naber & Siebers 1996)
Arrègle	[illegible]	(Arregle et al. 1999)



Modélisation

Transport (Lagrangien)

$$\frac{dm_g}{dt} = -\Gamma_{gm}$$

$$\frac{dm_g\vec{u}_g}{dt} = \vec{F}_g + m_g\vec{g}$$

$$\frac{dm_g T_g}{dt} = \frac{1}{Cp_g}(\Phi_{mg} - \Gamma_{gm} L_g)$$

Modélisation

Transport (Eulerien)

$$f\left(x,y,z,u,v,w,r,e,\dots\right) \qquad n = f\,dV$$

dV=dx.dy.dz.du.dv.dw.dz.dr.de….

$$\frac{\partial f^{(k)}}{\partial t}+\frac{\partial u_{lj} f^{(k)}}{\partial x_j}+\frac{\partial a_{lj} f^{(k)}}{\partial u_{lj}}+\frac{\partial\left(\frac{dr}{dt} f^{(k)}\right)}{\partial r}+\frac{\partial\left(\frac{de_l}{dt} f^{(k)}\right)}{\partial e_l}=\sum f_s$$

$$a_{li}=\frac{F_{D_i}}{\frac{4}{3}\pi\rho_l r^3}+g_i\left(1-\frac{\rho_a}{\rho_l}\right)+\frac{\rho_a}{\rho_l}\frac{du_i}{dt}=\frac{du_{li}}{dt}$$

$$\frac{de}{dt}=\frac{\dot{m}}{\frac{4}{3}\pi\rho_l r^3}\left(e_l-e_{ls}+\frac{\dot{q}}{\dot{m}}\right)+\frac{B^{(k)}}{\rho_l\psi^{(k)}}$$

l liquid, s surface, a air, u_i velocity components,

x_i spatial coordinates, r radius, e energy, g_i volume forces,

$\dot{m}$ evaporated mass flow rate, $\dot{q}$ conductive heat flux,

B energy flux, ψ the liquid volume fraction, ρ density.

•Sirignano W.A. – Fluid dynamics and transport of droplets and sprays – *Cambridge university press ISBN 052163036*, 1999, p.158

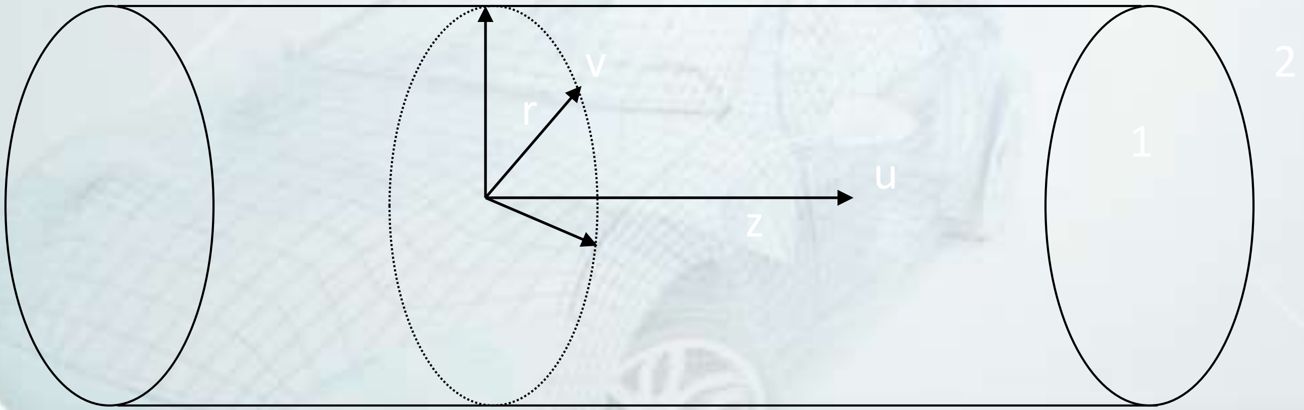
Wave

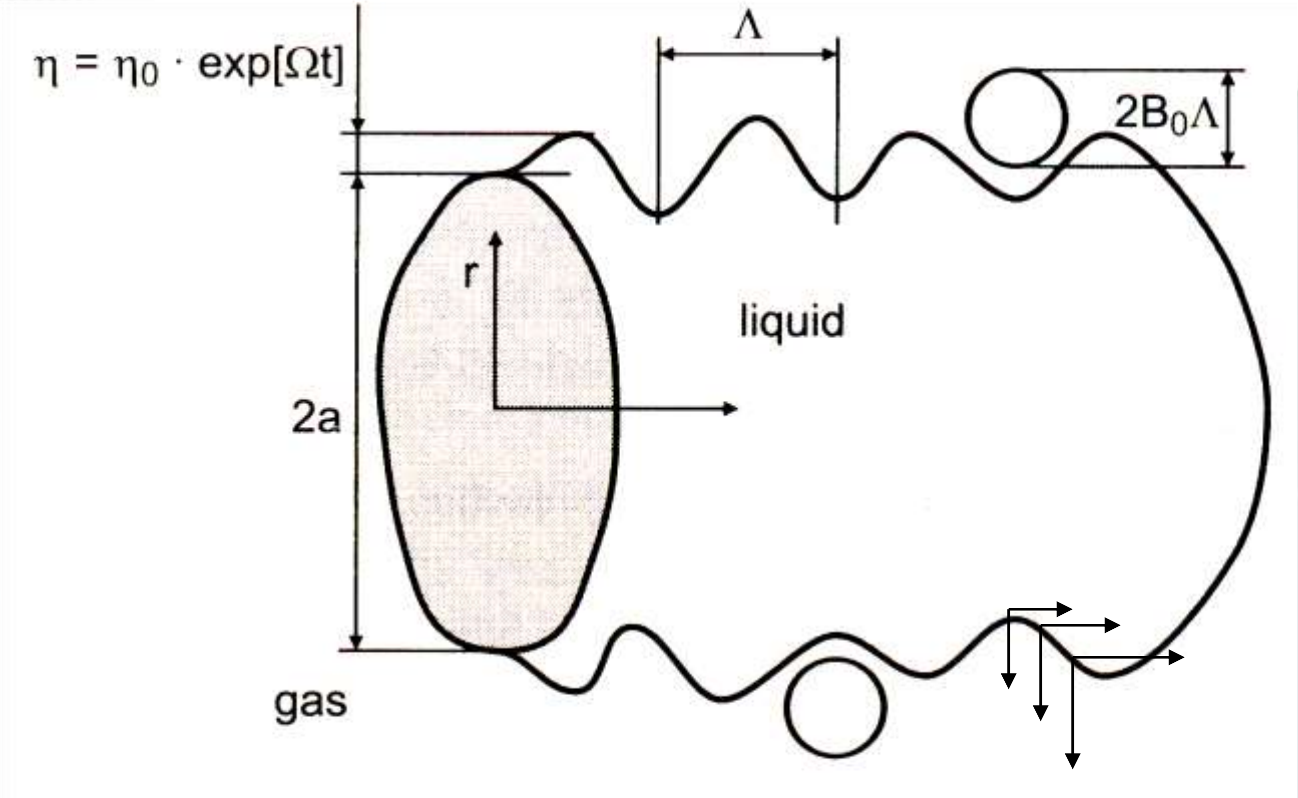
$$\frac{\partial u_i}{\partial z}+\frac{1}{r}\frac{\partial}{\partial r}\left(r v_i\right)=0$$

Equations N-S en coordonnées cylindriques pour deux milieux (1 et 2)

$$\frac{\partial u_i}{\partial t}+u_i(r)\frac{\partial u_i}{\partial z}+v_i\frac{\partial u_i}{\partial r}=-\frac{1}{\rho_i}\frac{\partial p_i}{\partial z}+\nu_i\left[\frac{\partial^2 u_i}{\partial z^2}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_i}{\partial r}\right)\right]$$

$$\frac{\partial v_i}{\partial t}+u_i(r)\frac{\partial v_i}{\partial z}=-\frac{1}{\rho_i}\frac{\partial p_i}{\partial r}+\nu_i\left[\frac{\partial^2 v_i}{\partial z^2}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_i}{\partial r}\right)\right]$$





$$v_i = \frac{\partial \eta}{\partial t} + u_i \frac{\partial \eta}{\partial z}$$

$$-p_1 + 2\mu_1 \frac{\partial u_1}{\partial z} - \frac{\sigma}{a^2}\left(\eta + a^2 \frac{\partial^2 \eta}{\partial z^2}\right) = -p_2$$

$$\frac{\partial u_1}{\partial r} = -\frac{\partial v_1}{\partial z}$$

Wave

$$\phi_1 = C_1 I_0(kr)\, e^{(ikz+\omega t)} \text{ et } \psi_1 = C_2\, r\, I_1(lr)\, e^{(ikz+\omega t)}$$

$U_2(r) = U$

$$p_2 = -\rho_2\left(U - i\frac{\omega}{k}\right)^2 k\eta\, \frac{K_0(ka)}{K_1(ka)}$$

R. D. Reitz, \Modelling atomization processes in high pressure vaporizing sprays, Atomisation and Spray Technology, vol. 3, pp. 309{337, 1987

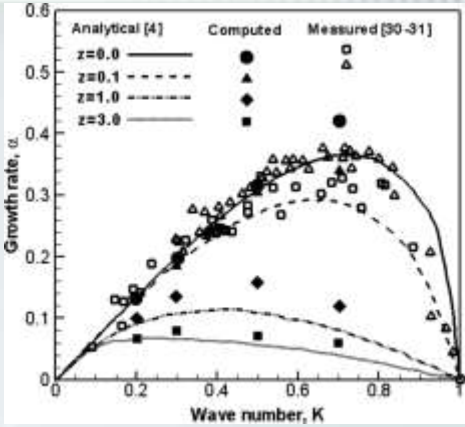
$$\begin{aligned}
&\omega^2 + 2\nu_1 k^2 \omega \left[\frac{I_1'(ka)}{I_0(ka)} - \frac{2k\ell}{k^2+\ell^2}\,\frac{I_1(ka)}{I_0(ka)}\,\frac{I_1'(\ell a)}{I_0(\ell a)}\right] \\
&= \frac{\sigma k}{\rho_1 a^2}(1-k^2a^2)\left(\frac{\ell^2-k^2}{\ell^2+k^2}\right)\frac{I_1(ka)}{I_0(ka)} \\
&+ \frac{\rho_2}{\rho_1}(U - i\omega/k)^2 k^2 \left(\frac{\ell^2-k^2}{\ell^2+k^2}\right)\frac{I_1(ka)K_0(ka)}{I_0(ka)K_1(ka)}
\end{aligned}$$

Rayleigh

Wave

$ka \rightarrow \infty$

$$(\omega + 2\nu_1 k^2)^2 + \frac{\sigma k^3}{\rho_1} - 4\nu_1^2 k^3 \sqrt{k^2 + \frac{\omega}{\nu_1}} + (\omega + iUk)^2 \frac{\rho_2}{\rho_1} = 0$$



$$\frac{\Lambda}{a} = 9{,}02 \frac{(1+0{,}45 Z^{0{,}5})(1+0{,}47\, T^{0{,}7})}{(1+0{,}87\, We_2^{1{,}67})^{0{,}6}}$$

$$\Omega \left(\frac{\rho_1 a^3}{\sigma}\right)^{0{,}5} = \frac{0{,}34 + 0{,}38\, We_2^{1{,}5}}{(1+Z)(1+1{,}4 T^{0{,}6})}$$

$$Z = \frac{We_1^{0{,}5}}{Re_1}\;;\quad T = Z We_2^{0{,}5}\;;\quad We_1 = \frac{\rho_1 U^2 a}{\sigma};\quad We_2 = \frac{\rho_2 U^2 a}{\sigma}\;;\quad Re_1 = \frac{Ua}{\nu_1}$$

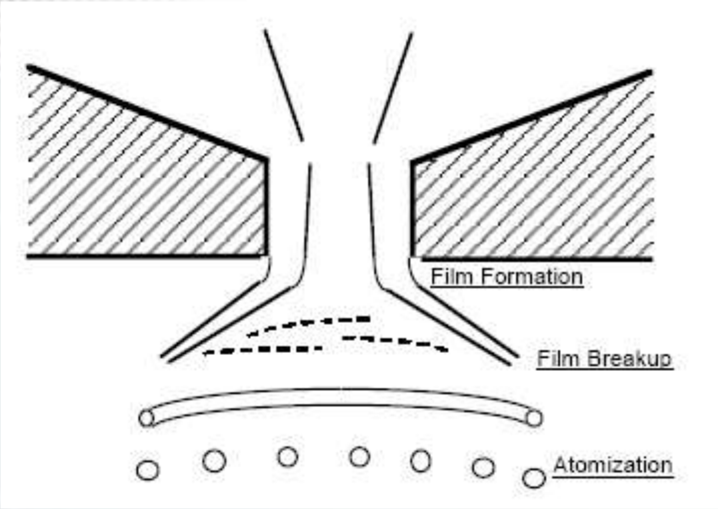
$$r_d = B\Lambda$$

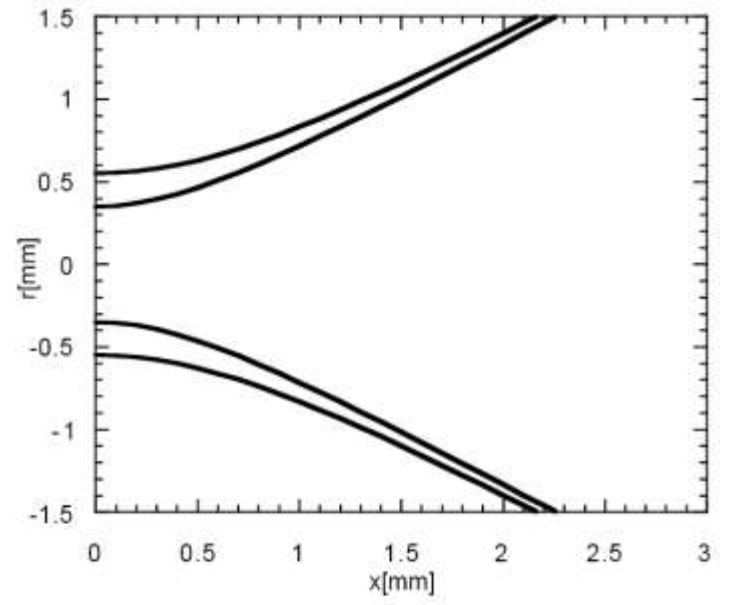
$$L = \frac{c\,a}{f(\mathrm{T})} \sqrt{\frac{\rho_l}{\rho_g}}$$

$$\tan\left(\frac{\alpha}{2}\right) = \frac{v_\perp}{U} = \frac{\Omega\Lambda}{AU} = \frac{4\pi}{A} \sqrt{\rho_g / \rho_l}\, f(\mathrm{T})$$

$$A = 3.0 + \frac{l_{noz} / d_{noz}}{3.6}$$

Equations N-S en coordonnées cylindriques pour une nappe conique d’épaisseur variable





$$\omega^2\left[\tanh(kh)+Q\right]+\left[4\nu_l k^2\tanh(kh)+2iQkU\right]+$$

$$4\nu_l k^4\mathit{tahn}(kh)-4\nu_l^2k^3\ell\tanh(\ell h)-QU^2k^2+\frac{\sigma k^3}{\rho_l}=0$$

Linéarisation :

$$\omega_r=-2\nu_l k^2+\sqrt{4\nu_l^2k^4+QU^2k^2-\frac{\sigma k^3}{\rho_l}}$$

D. P. Schmidt, I. Nouar, P. K. Senecal, C. J. Rutland, J. K. Martin, and R. D. Reitz.
Pressure-Swirl Atomization in the Near Field.
SAE Paper 01-0496, SAE, 1999

P. K. Senecal, D. P. Schmidt, I. Nouar, C. J. Rutland, and R. D. Reitz.
Modeling High Speed Viscous Liquid Sheet Atomization.
International Journal of Multiphase Flow, in pres

$$\eta_b = \eta_0 \exp(\Omega\tau) \Rightarrow \tau = \frac{1}{\Omega}\ln\left(\frac{\eta_b}{\eta_0}\right)$$

$$L = U\tau = \frac{U}{\Omega}\ln\left(\frac{\eta_b}{\eta_0}\right)$$

$$h = \frac{\dot{m}}{2\pi\rho U\left(\delta + 2L\sin(\theta)\right)}$$

$$K_L d_L = \left[\frac{1}{2} + \frac{3\mu_l}{2\left(\rho_1 \sigma d_L\right)^{1/2}}\right]^{-\frac{1}{2}}$$

$$d_L = \sqrt{\frac{16h}{K_s}}$$

$$d_D^3 = \frac{3\pi d_L^2}{K_L}$$

Modélisation

Modèle eulerien

Equation de transport pour l'aire moyenne de l'interface luiquide/gaz par unité de volume

$$\frac{\partial\bar{\Sigma}}{\partial t}+\frac{\partial\tilde{u}_i\bar{\Sigma}}{\partial x_i}=\frac{\partial\left(D_s\frac{\partial\bar{\Sigma}}{\partial x_i}\right)}{\partial x_i}+\left(A+a\right)\bar{\Sigma}-V_a\bar{\Sigma}^2$$

(= diffusion + production – destruction)

$$We_c=\frac{\rho_g r_c u_c{}^2}{\sigma}\,\square\,1$$

Vallet A., Burluka A.A., Borghi R., 2001, Development of an Eulerian model for the atomization of a liquid jet, *Atomization and Sprays*, 2001, 11 (6), 619-642

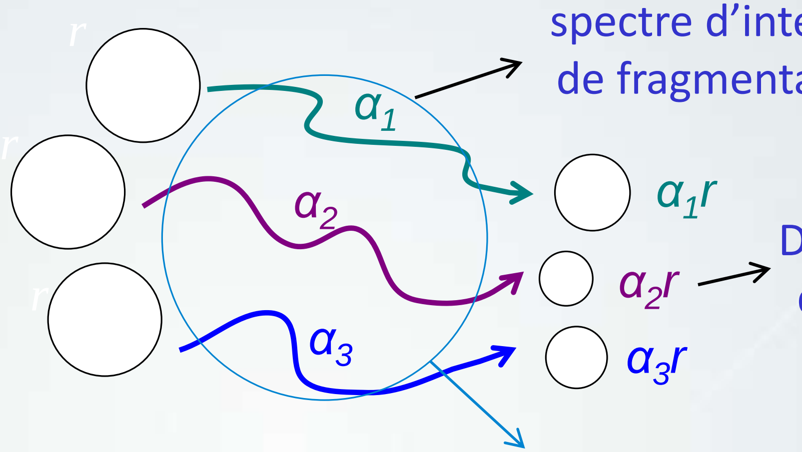
Modélisation

Modèle probabiliste

M. Gorokhovski & V. Saveliev. Further Analyses of Kolmogorov's Model of Breakup. Physics of Fluids, 15(1): 184-192, 2003

Échelle de longueur *r*

$r \longrightarrow \alpha r$ Avec $0<\alpha<1$



spectre d'intensité de fragmentation $\rightarrow q(\alpha)$

Distribution d'échelles $\rightarrow f(r)$

Phénomènes physiques complexes

Équation d'évolution

$$\frac{\partial f(r)}{\partial t} = \nu \int f\left(\frac{r}{\alpha}\right) q(\alpha) \frac{d\alpha}{\alpha} - \nu f(r)$$

Fréquence

Spectre d'intensité de fragmentation

Modélisation

Modèle probabiliste

M. Gorokhovski, J.Jouanguy, A.Chtab (2009) Stochastic model of the near-to-injector spray formation assisted by high-speed coaxial gas jet Fluid dynamics research 41 (3), 035509

Forme exacte aux temps longs

r

Équation de type Fokker-Planck

$$\frac{\partial f(r,t)}{\partial t} = \left[-\frac{\partial}{\partial r} r\langle \ln\alpha\rangle + \frac{1}{2}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} r\langle \ln^2\alpha\rangle\right]$$

Deux paramètres

→ Fonction de distribution des fragments
Phase d'atomisation secondaire

Équation de type Langevin

$$\frac{\partial r}{\partial t} = \nu\langle \ln\alpha\rangle + \sqrt{\nu\frac{\langle \ln^2\alpha\rangle}{2}}\, r\Gamma(t)$$

→ Position de l'interface liquide/gaz
Phase d'atomisation primaire

$$\langle \ln\alpha\rangle = const.\ln\left(\frac{r_*}{r_0}\right)$$

$$\frac{\langle \ln^2\alpha\rangle}{\langle \ln\alpha\rangle} = \ln\left(\frac{r_*}{r_0}\right)$$

→ r_* = échelle de longueur typique après fragmentation
r_0 = échelle de longueur typique après fragmentation

Modèle probabiliste – Application à l’atomisation assistée par air

M. Gorokhovski, J.Jouanguy, A.Chtab (2009) Stochastic model of the near-to-injector spray formation assisted by high-speed coaxial gas jet Fluid dynamics research 41 (3), 035509

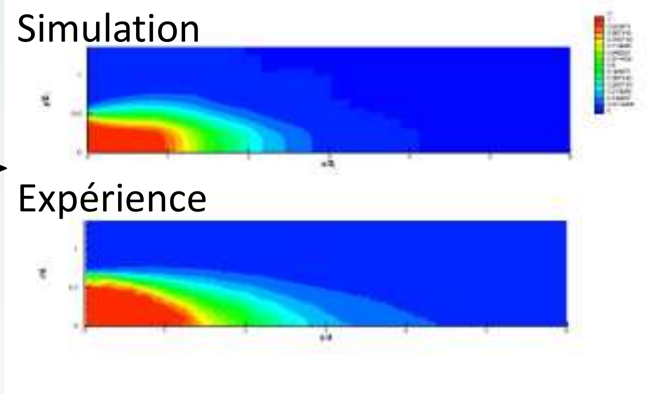
Couplage LES pour l’atomisation assitée par air

Atomisation primaire → Cœur liquide & Probabilité de présence de liquide non fragmenté →

Equation de Langevin

$r_* = \lambda_{RT}$

$r_0 = \lambda_{KH}$

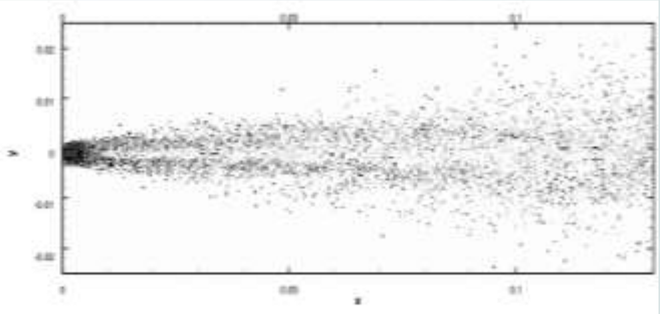


$u_g = 180\ m/s,\ u_l = 2.03\ m/s$

Injection de gouttes et suivi Lagrangien

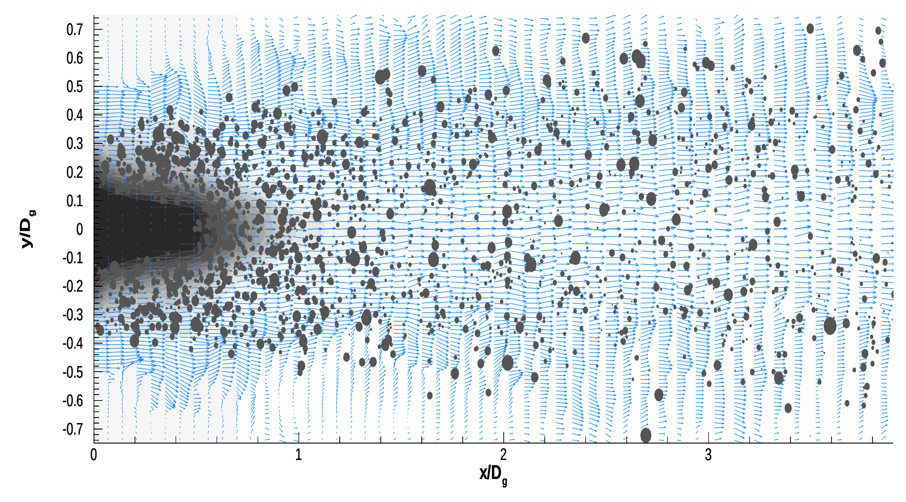
Atomisation secondaire → Fragmentations ou coalescences liées aux collisions →

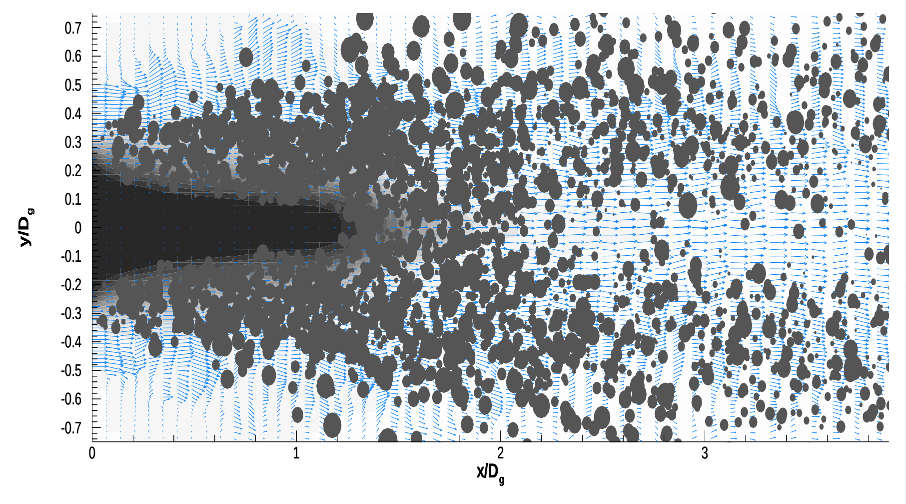
Equation de Fokker-Planck



Modèle probabiliste – Application à l'atomisation assistée par air

M. Gorokhovski, J.Jouanguy, A.Chtab (2009) Stochastic model of the near-to-injector spray formation assisted by high-speed coaxial gas jet Fluid dynamics research 41 (3), 035509





u_g = 140 m/s
u_l = 0.33 m/s

u_g = 140 m/s
u_l = 2.8 m/s

Augmentation de la taille des gouttes et de la longueur du cœur liquide en fonction de la vitesse du liquide à vitesse de gaz constante

Simulation numérique

Simulation numérique directe : méthodes de suivi d’interface

Méthode Level-set

Fonction level-set φ(x) définie telle que l’interface Γ soit le lieux où φ est nulle dans une région Ω

OSHER (S.) et FEDKIW (R.P.). – *Level set methods : An overview and some recent results.* Journal of Computational Physics, vol. 169, Issue 2, p. 463-502, mai 2001.

$$\Gamma\ (t) = \{x | \varphi\ (x, t) = 0\}$$

$$x \in \Omega \rightarrow \varphi\ (x, t) > 0$$

$$x \notin \Omega \rightarrow \varphi\ (x, t) < 0$$

$$x \in \partial\Omega = \Gamma \rightarrow \varphi\ (x, t) = 0$$

Fonction convectée par le champ de vitesse

$$\frac{\partial \varphi}{\partial t} + v \nabla \varphi = 0$$

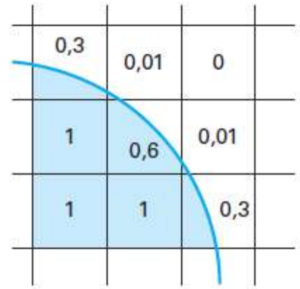
Méthode VOF (Volume of fluid)

HIRT (C.W.) et NICHOLS (B.D.). – *Volume of fluid (VOF) method for the dynamics of free boundaries.* J. Comput. Phys., vol. 39, p. 201.

Variation de la fraction volumique de liquide F en fonction des flux de liquide φ entrant et sortant de la maille

Variation de F entre deux pas de temps :

$$F_{ij}^{t+1} = F_{ij}^{t} + \delta t\ [\Phi^{y}_{i,j-1/2} - \Phi^{y}_{i,j+1/2} + \Phi^{x}_{i-1/2,j} - \Phi^{x}_{i+1/2,j}]$$



La valeur du traceur représente la fraction volumique de liquide (bleu) dans le gaz (blanc)

Simulation numérique

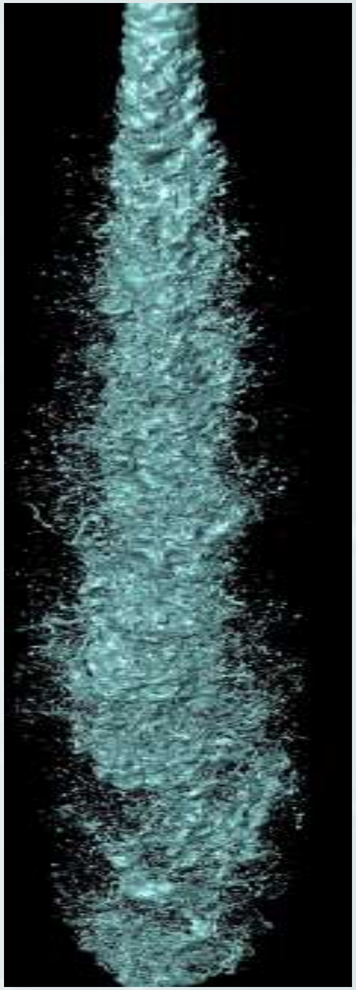
Simulation numérique directe : méthode Level Set

Approche Eulérienne reposant sur la résolution d'une équation de transport de la fonction Level set

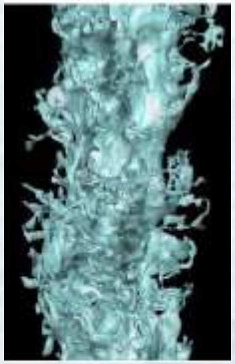
Fonction continue : distance à l'interface

« Expérimentations numériques » sur le spray

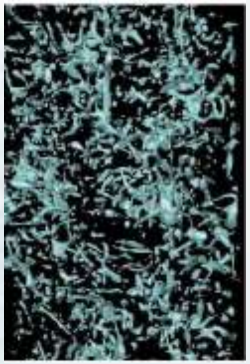
Ménard T., Tanguy S.,Berlemont A. Coupling Level Set / VOF / Ghost fluid methods :Validation and application to 3D simulation of jet primary break-up Int. J. Multiphase Flows 33, 5, 510–524, 2007



Zoom sur une portion du spray



Cœur liquide



Gouttes

Simulation numérique

Simulation numérique directe : méthode VOF (Volume Of Fluid)

→ Approche Eulérienne reposant sur la résolution d’une équation de transport de la fraction de liquide

FUSTER (D.), BAGUE (A.), BOECK (T.), LE MOYNE (L.), LEBOISSETIER (A.), POPINET (S.), RAY (P.), SCARDOVELLI (R.) et ZALESKI (S.). – *Simulation of primary atomization with an octree adaptive mesh refinement and VOF method*. International Journal of Multiphase Flow, vol. 35, Issue 6, p. 550-565, juin 2009.

« Expérimentations numériques » sur le spray

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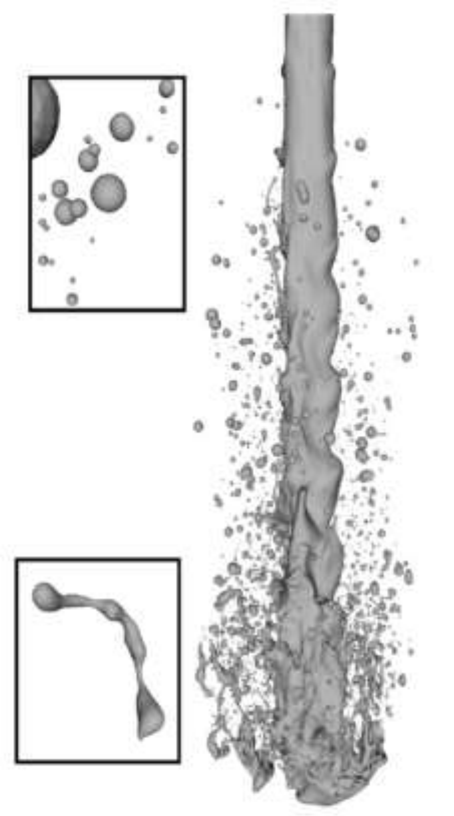
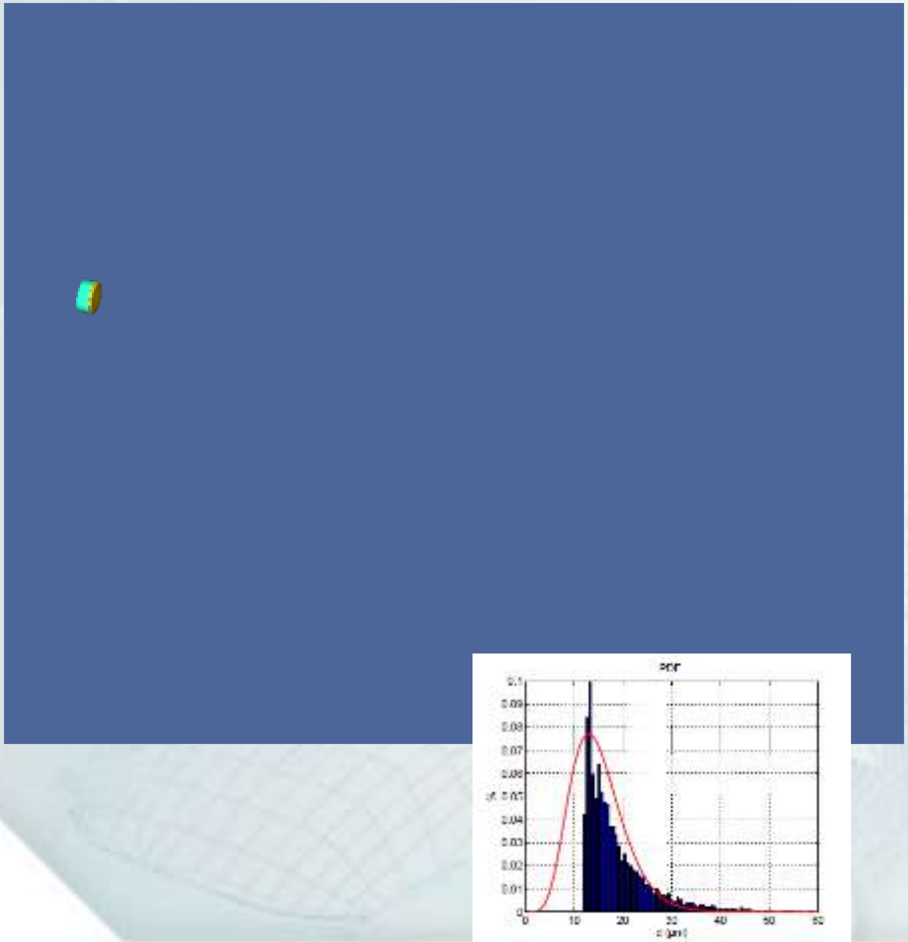


Vincent Le Chenadec, Heinz Pitsch (2013) A 3D Unsplit Forward/Backward Volume-of-Fluid Approach and Coupling to the Level Set Method . *Journal of Computational Physics*.

→ Nécessité d’une grande puissance de calcul pour la DNS

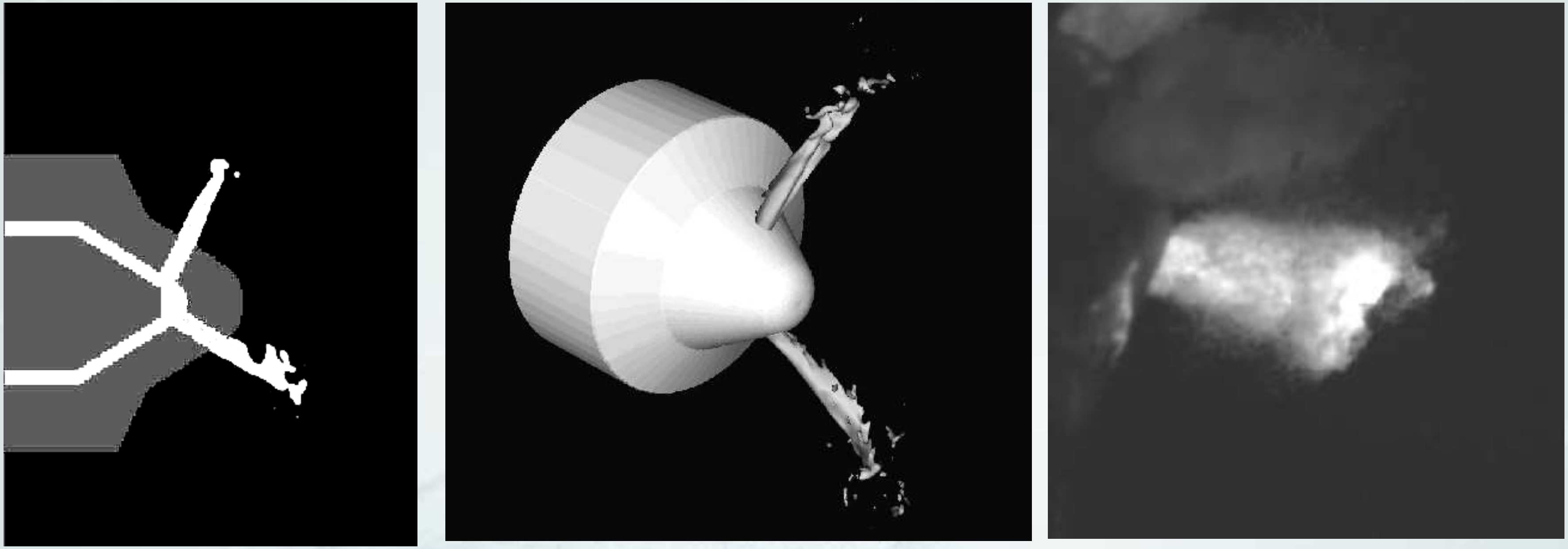
Simulation numérique

Simulation numérique directe : méthode VOF (Volume Of Fluid)



Simulation numérique

Simulation numérique directe : méthode VOF (Volume Of Fluid)



Simulation numérique

Simulation des grandes échelles

Approches Eulériennes

Labourasse et al. 2007
Vincent et al. 2008

→ Filtrage a priori → Nécessité de construire des modèles de sous maille spécifiques au voisinage de l'interface liquide/gaz

Approches Lagrangiennes

M. Gorokhovski et al. 2009
D. Kim & P. Moin 2011

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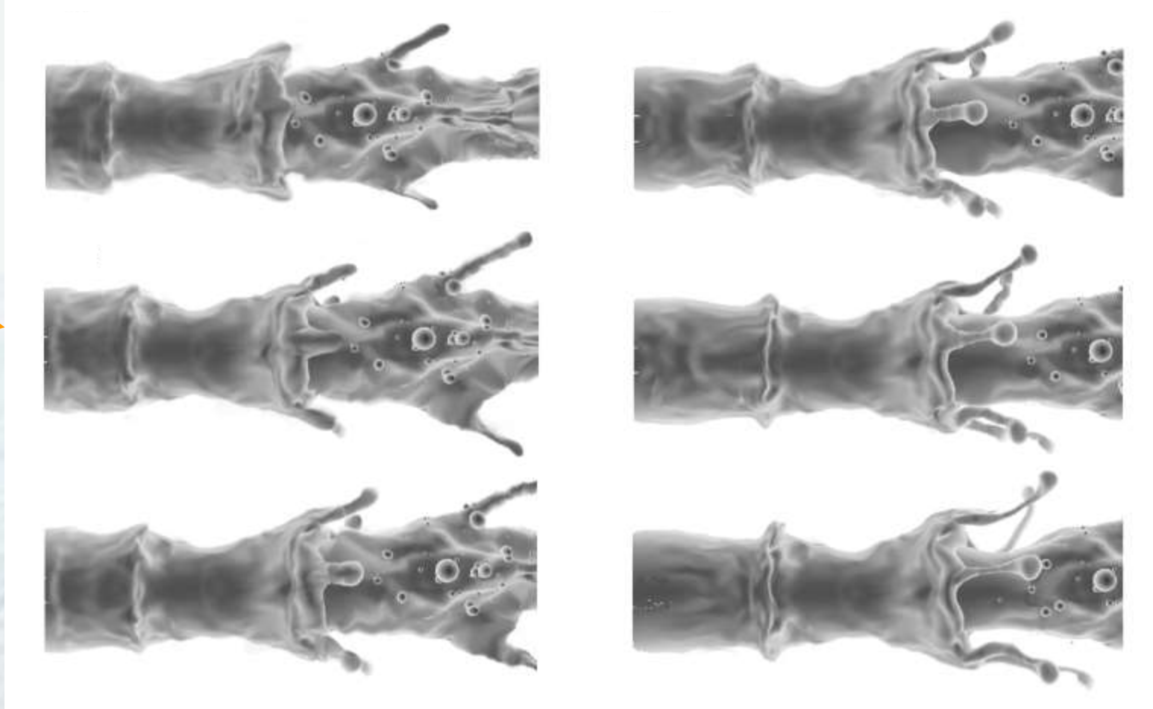
Formation de gouttes en sous-maille suivies de façon Lagrangienne



Simulation LES de la zone d'atomisation primaire assistée par air

Conclusion