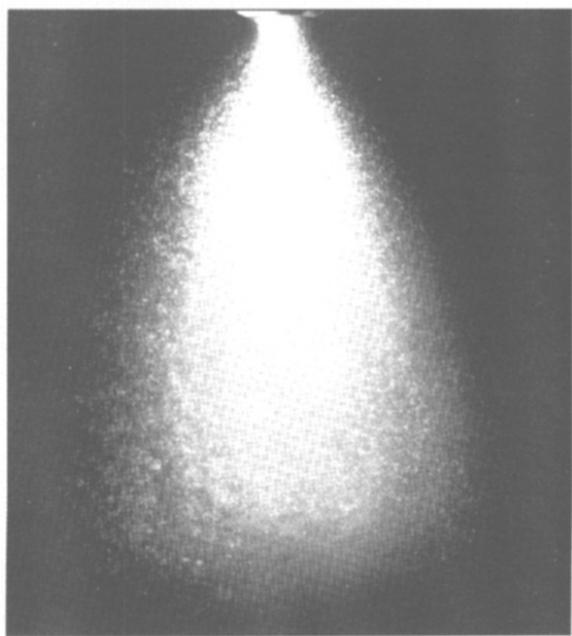
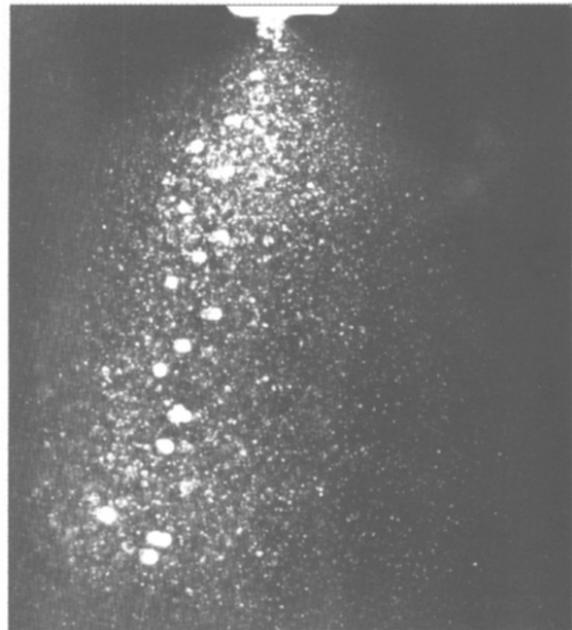
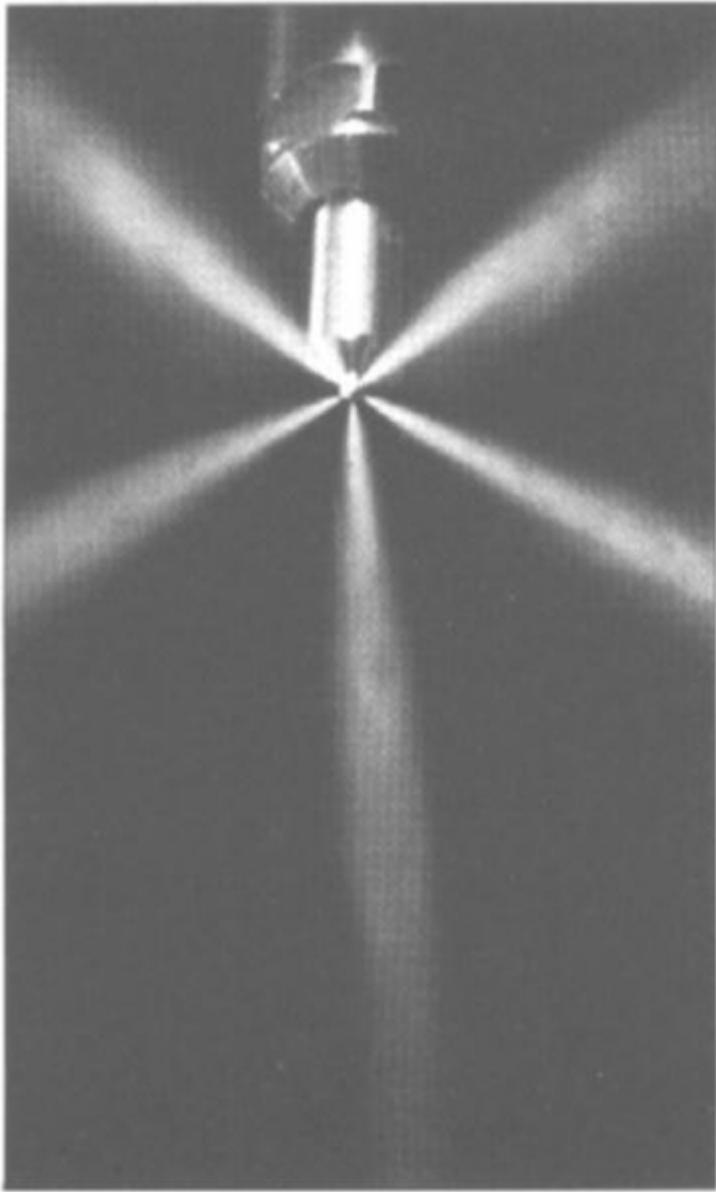
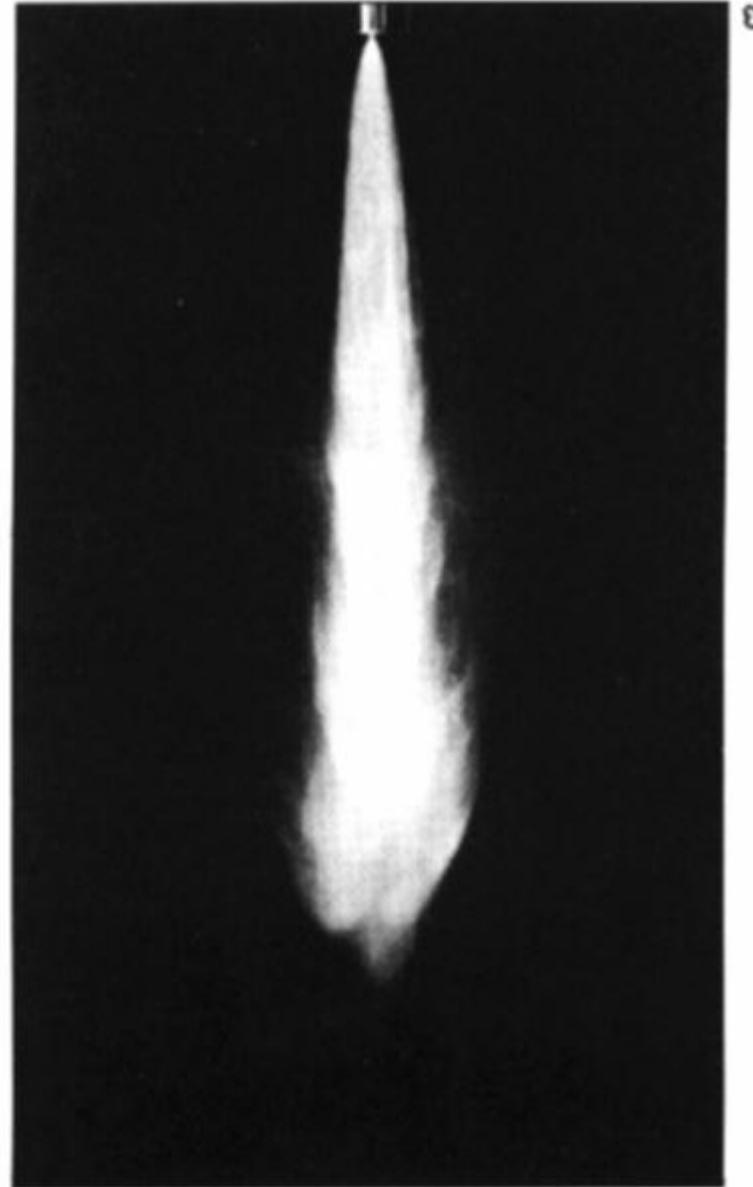
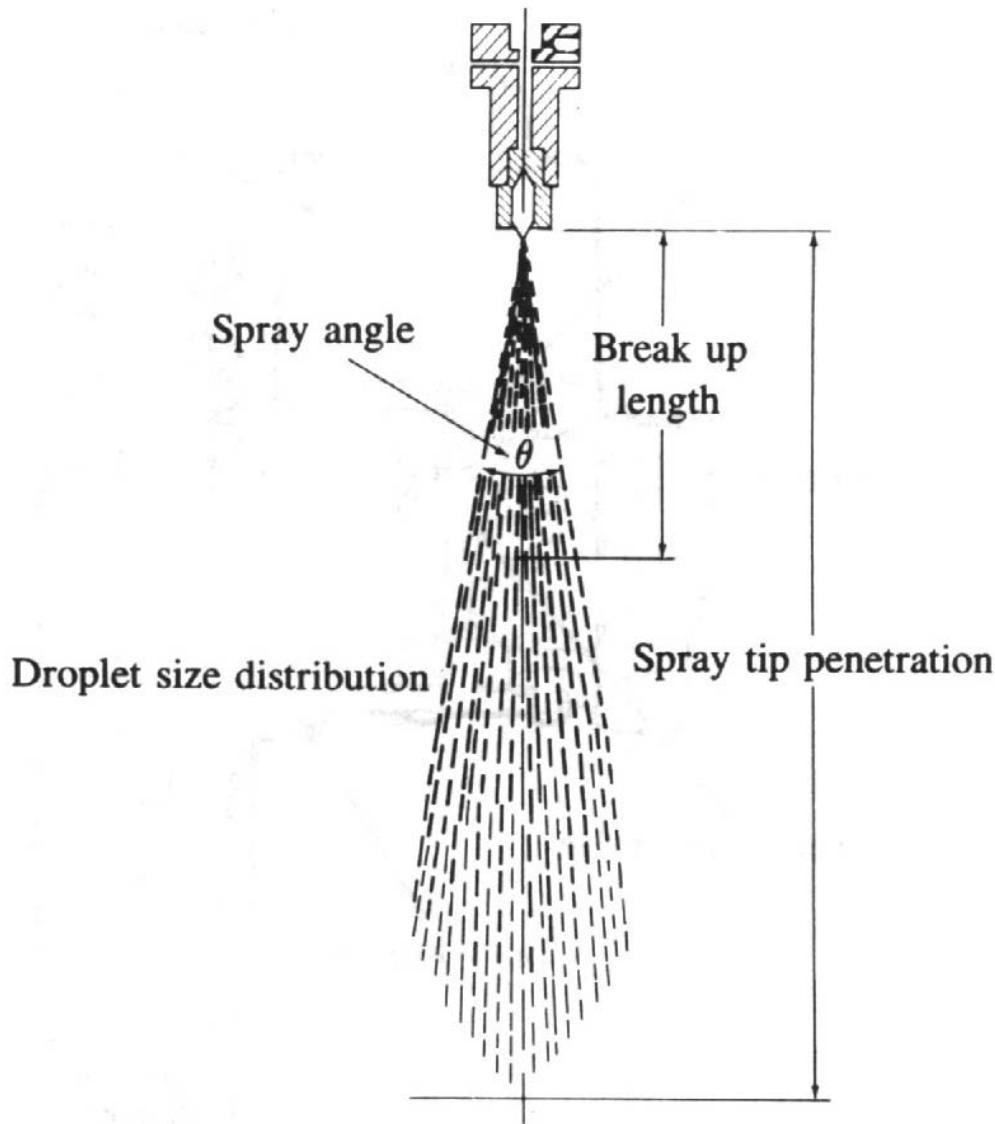
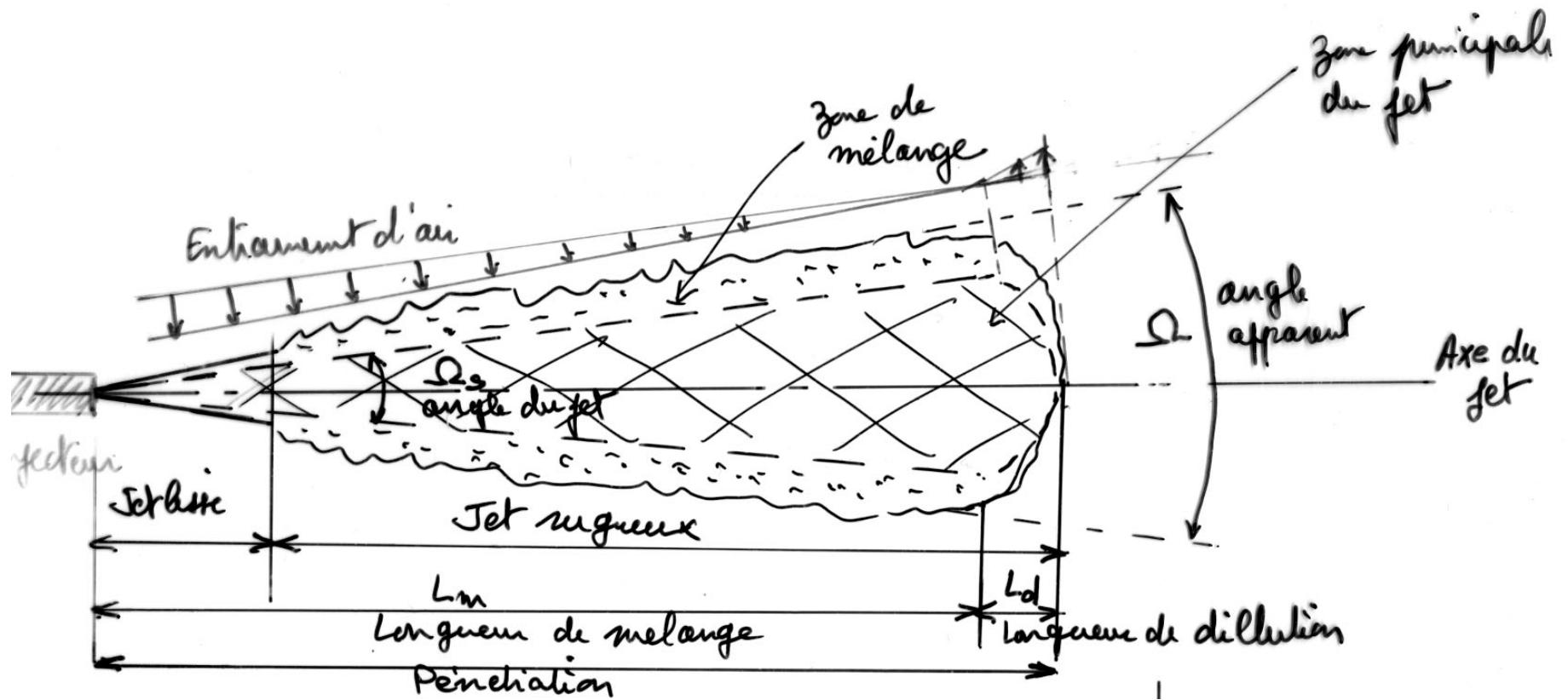


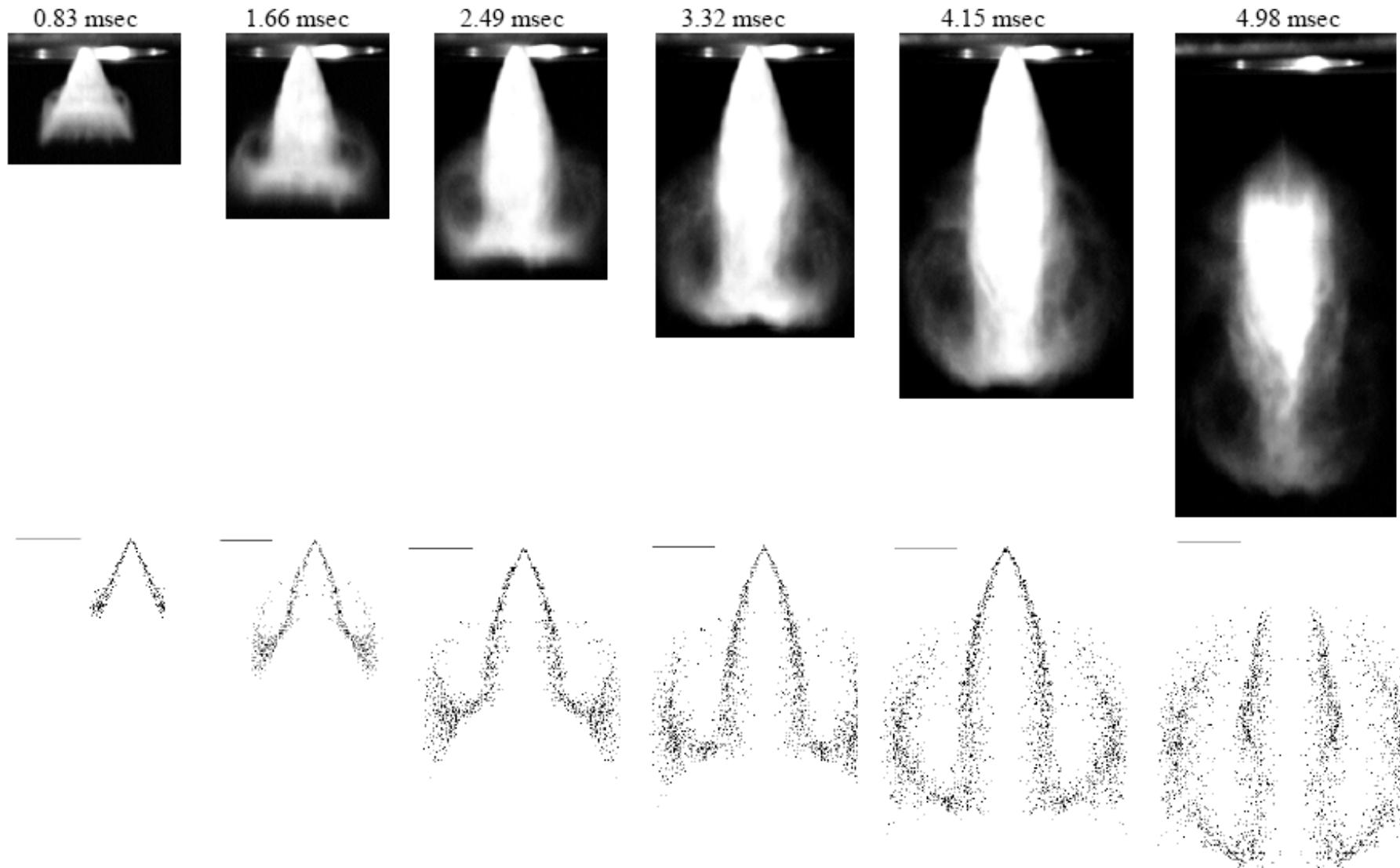
Atomisation

Principes - modélisation



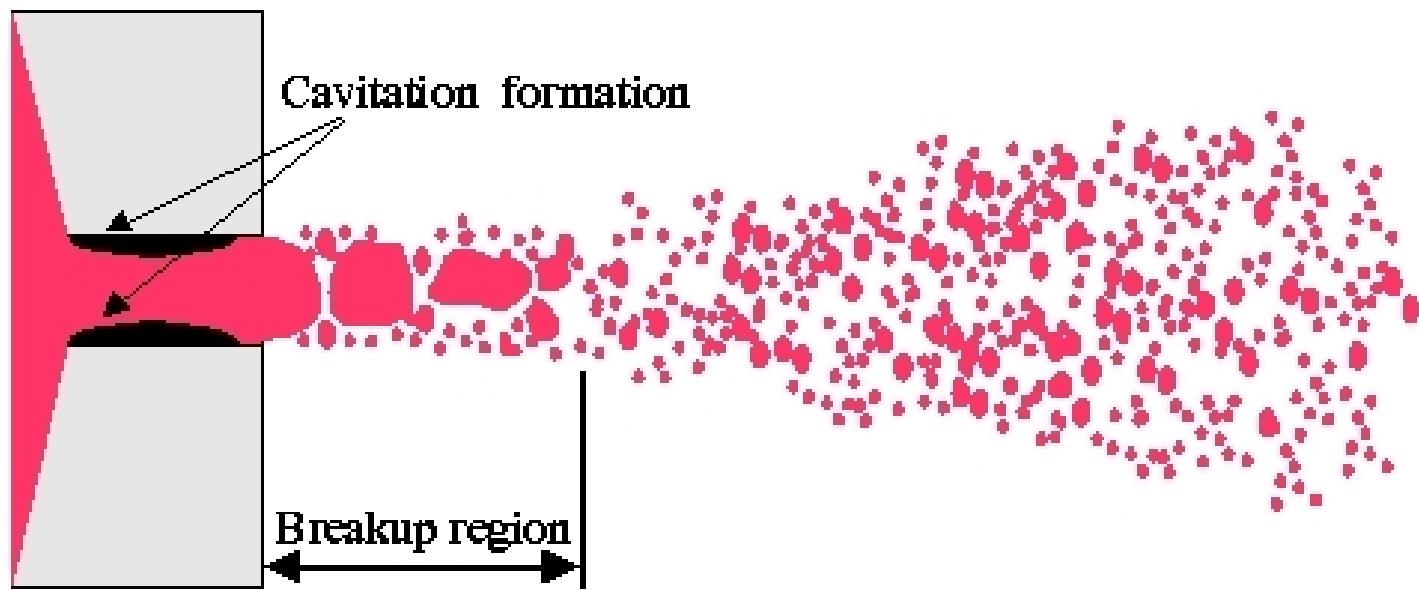
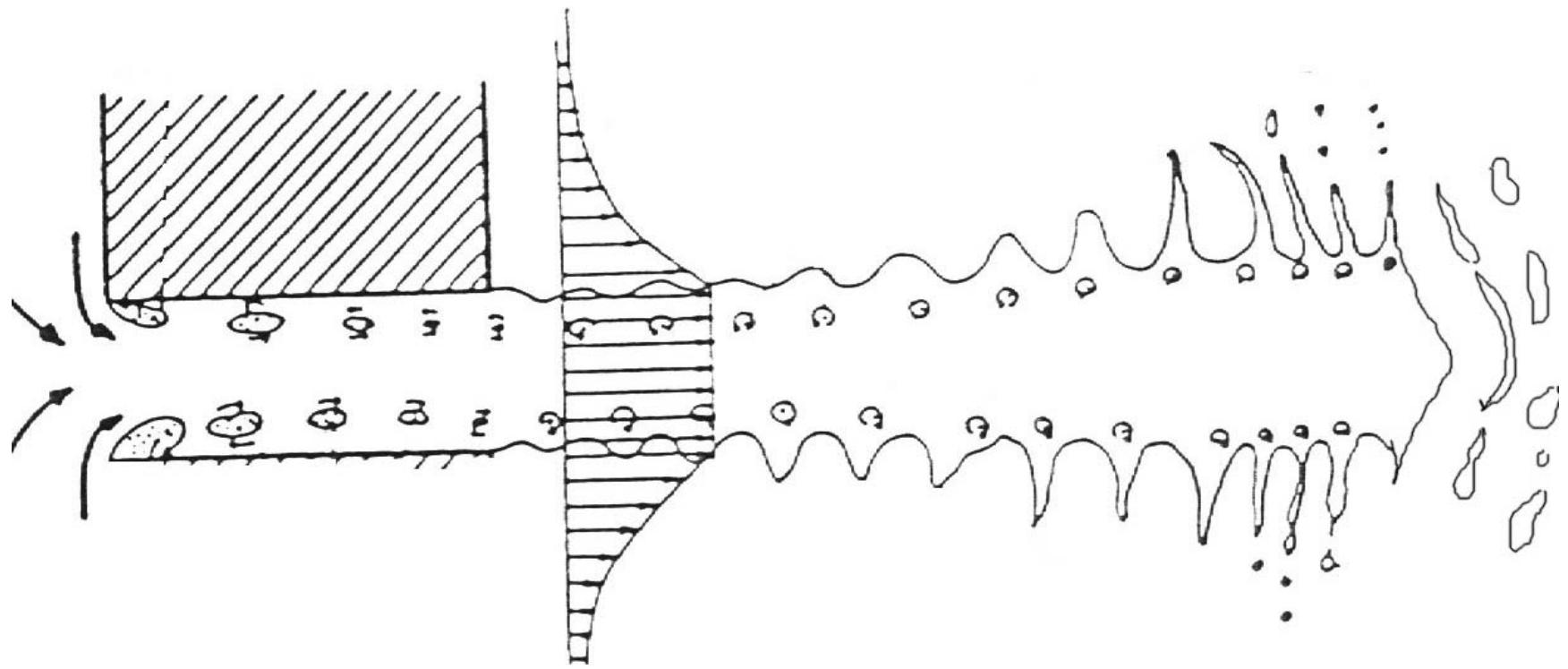




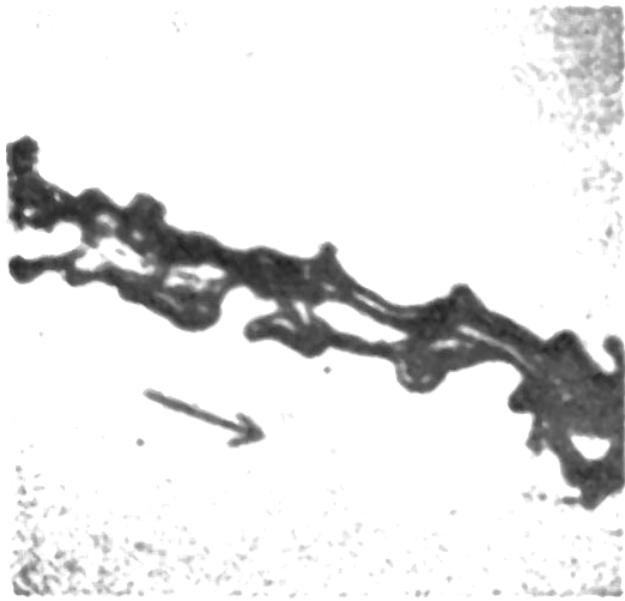
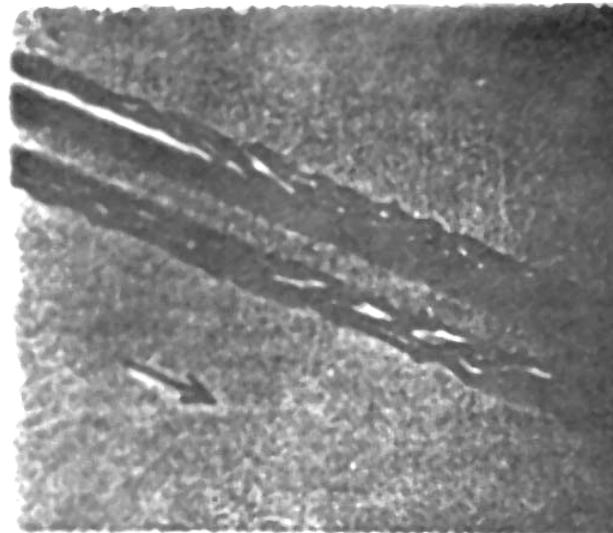
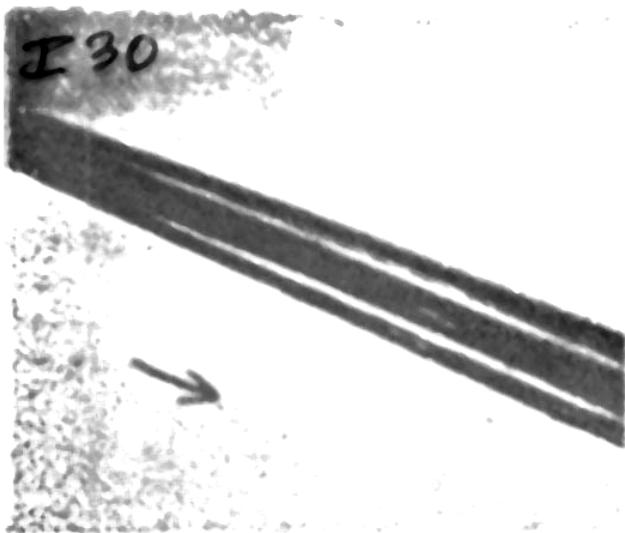


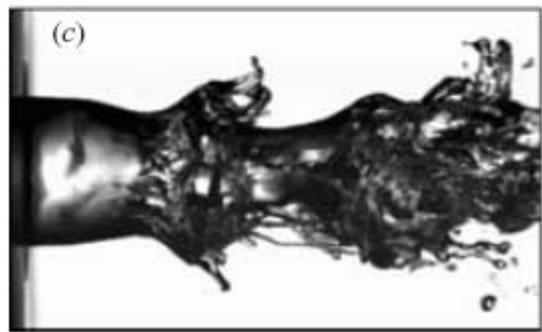
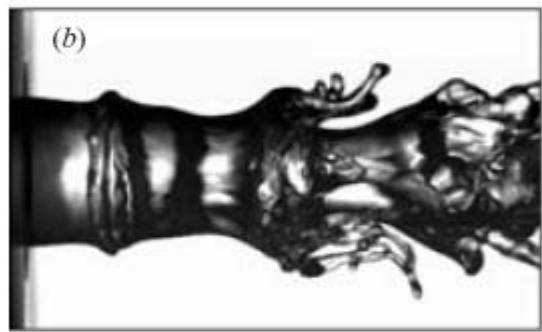
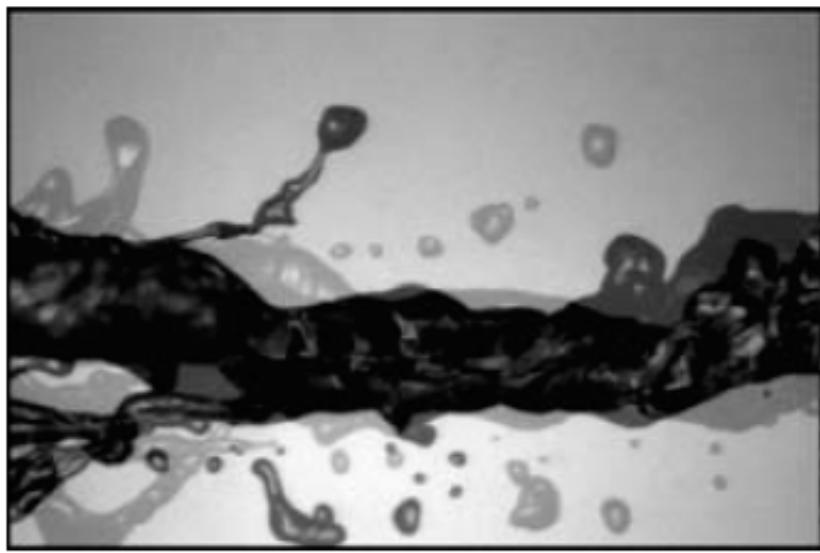
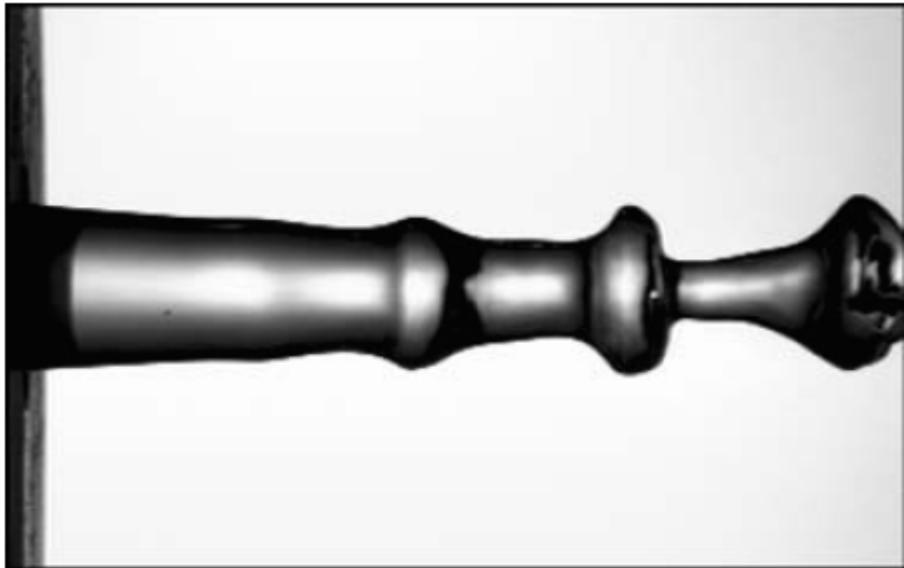
Pressure-Swirl Atomization in the Near Field

David P. Schmidt, Idriss Nouar, P. K. Senecal, Jeff Hoffman, C. J. Rutland, J. Martin, R. D. Reitz



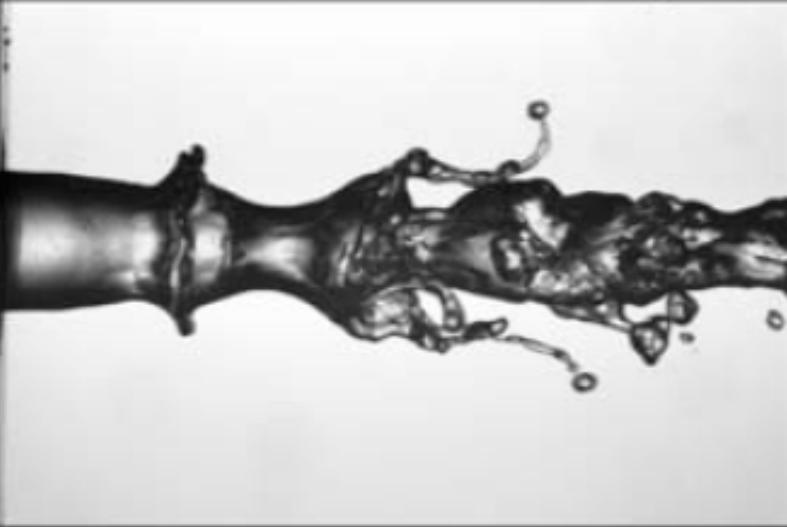
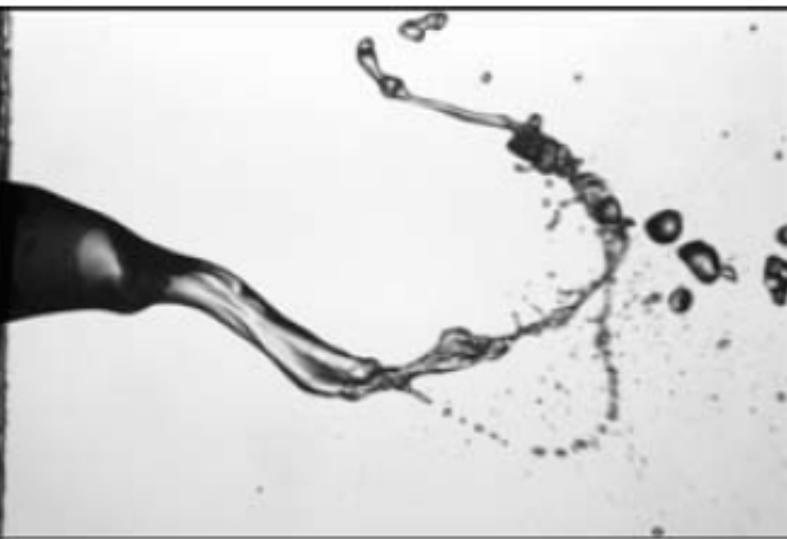
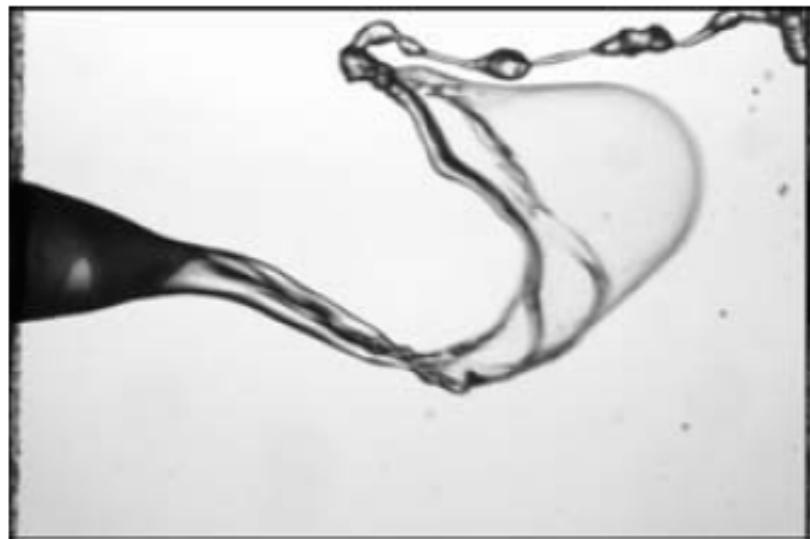
I³⁰



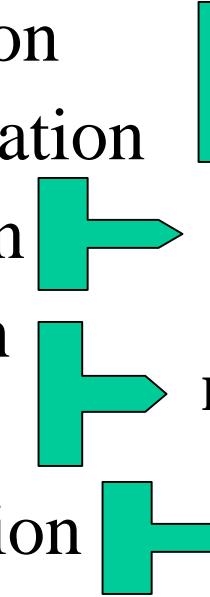


On spray formation

By P. MARMOTTANT AND E. VILLERMAUX



Atomiseurs & 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 »

Formation de gouttes

- (a) Liquid dripping – Goutte à goutte
- (b) Liquid column/jet breakup – Rupture de jet
- (c) Liquid ligament breakup – Rupture de ligament
- (d) Liquid sheet/film breakup – Rupture de nappe
- (e) Liquid free-surface breakup – Arrachement de surface libre

$$\mathrm{Re}_L = \rho_L U_L d_0 / \mu_L$$

$$Z=\mathrm{Oh}=\mathrm{We}_L^{0.5}\,\mathrm{Re}_L^{-1}=\frac{\mu_L}{(\rho_L\sigma d_0)^{0.5}}$$

$$\mathrm{We}_L=\frac{U_L^2\rho_Ld_0}{\sigma}$$

Rupture de jet

- Rayleigh (non visqueux)

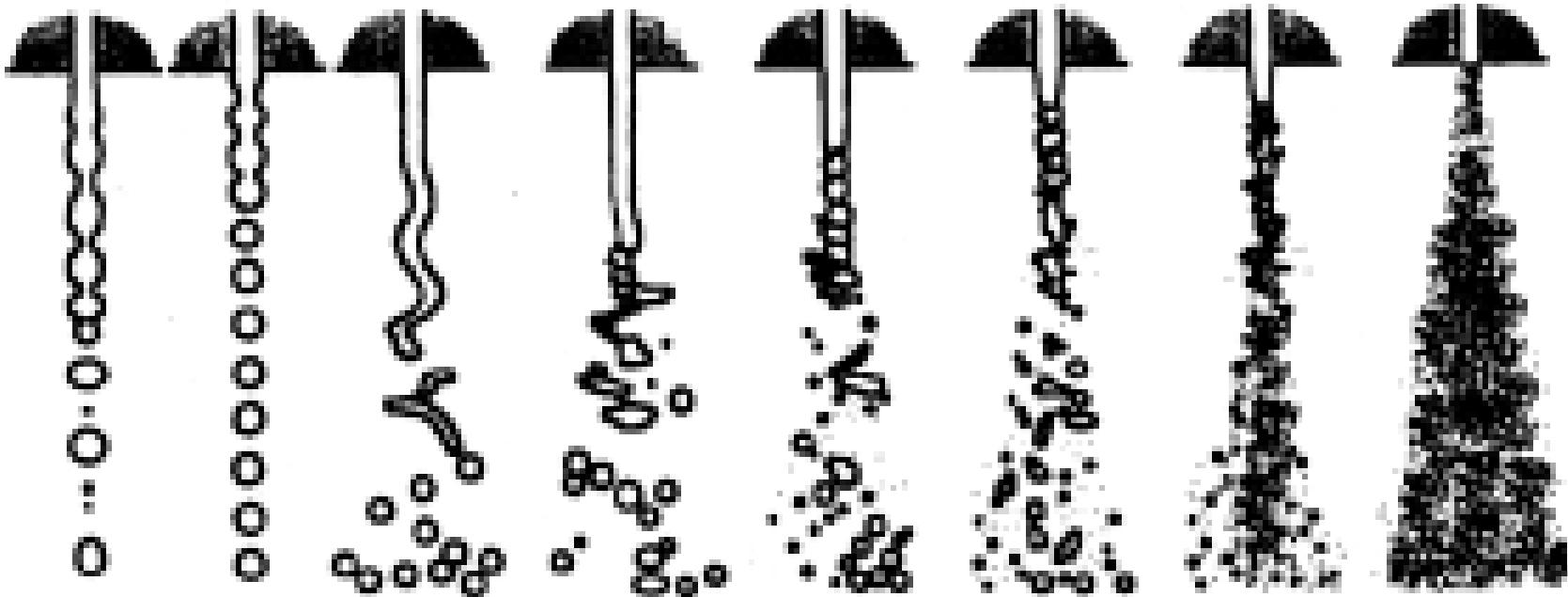
$$\lambda_{opt} = 4.51 d_0$$

$$D = 1.89 d_0$$

- Weber (visqueux)

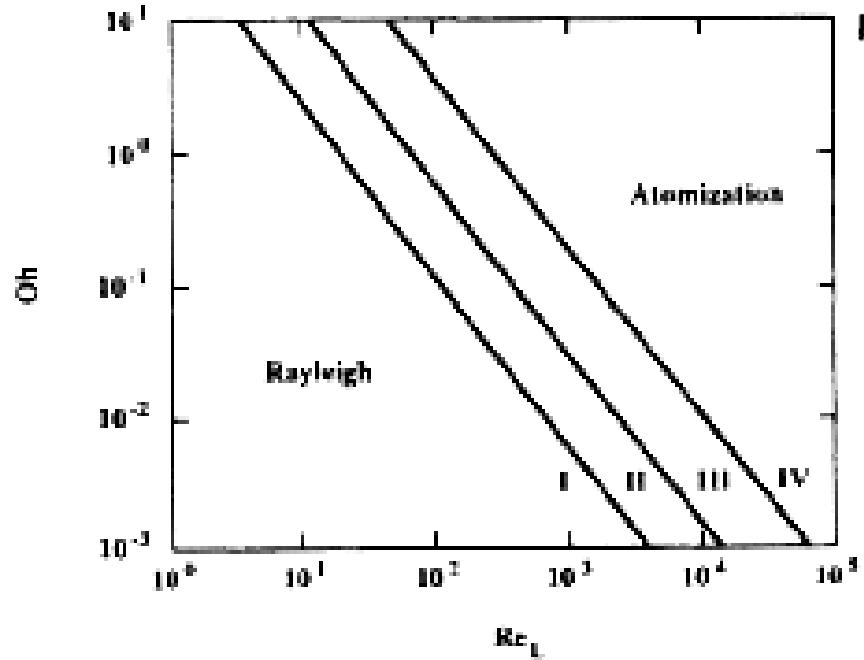
$$\lambda_{opt} = \begin{cases} 4.44 d_0 & \text{non-viscous liquids} \\ \sqrt{2\pi} d_0 \left(1 + \frac{3\mu_L}{\sqrt{\rho_L \sigma d_0}} \right)^{0.5} & \text{viscous liquids} \end{cases}$$

$$D = (1.5 \lambda_{opt} d_0^2)^{1/3}$$



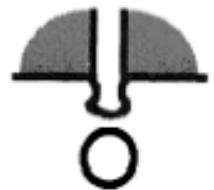
Mechanism of atomization of a liquid jet

R. D. Reitz and F. V. Bracco



Regime ^{[40][220][227]}	Predominant Breakup Mechanism ^{[40][227]}	Criteria ^{*[227]}
Rayleigh Jet Breakup (Varicose Breakup)	Surface Tension Force	$We_A < 0.4$ or $We_A < 1.2 + 3.41Oh^0.9$
First Wind-Induced Breakup (Sinuous Wave Breakup)	Surface Tension Force, Dynamic Pressure of Ambient Air	$1.2 + 3.41Oh^0.9 < We_A < 13$
Second Wind-Induced Breakup (Wave-like Breakup with Air Friction)	Dynamic Pressure of Ambient Air	$13 < We_A < 40.3$
Atomization	Unknown, but Plausibly: Aerodynamic Interaction, Turbulence, Cavitation, Bursting Effect	$We_A > 40.3$ or $Oh \geq 100 Re_L^{-0.92}$ <small>[220]</small>

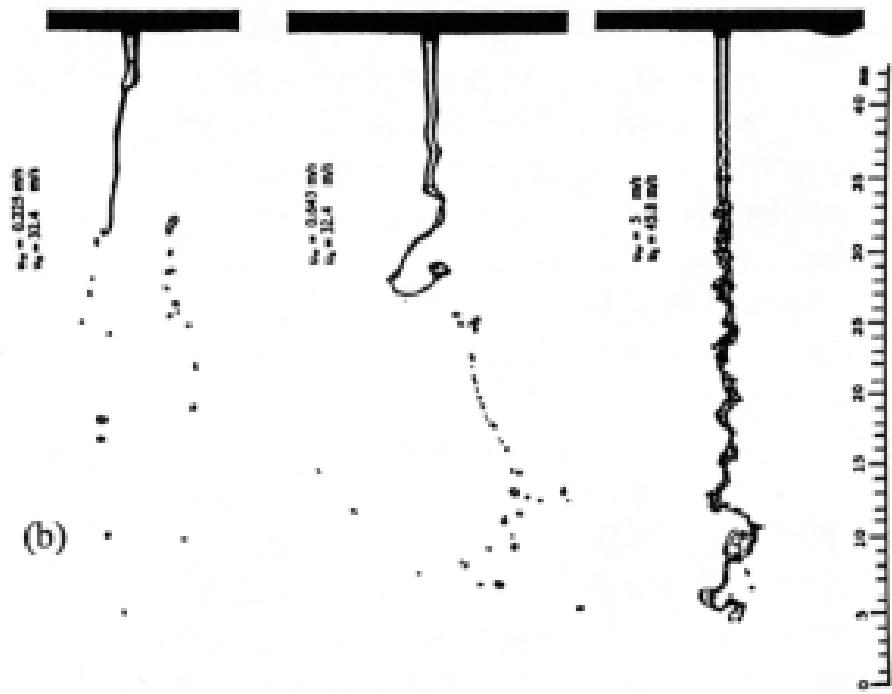
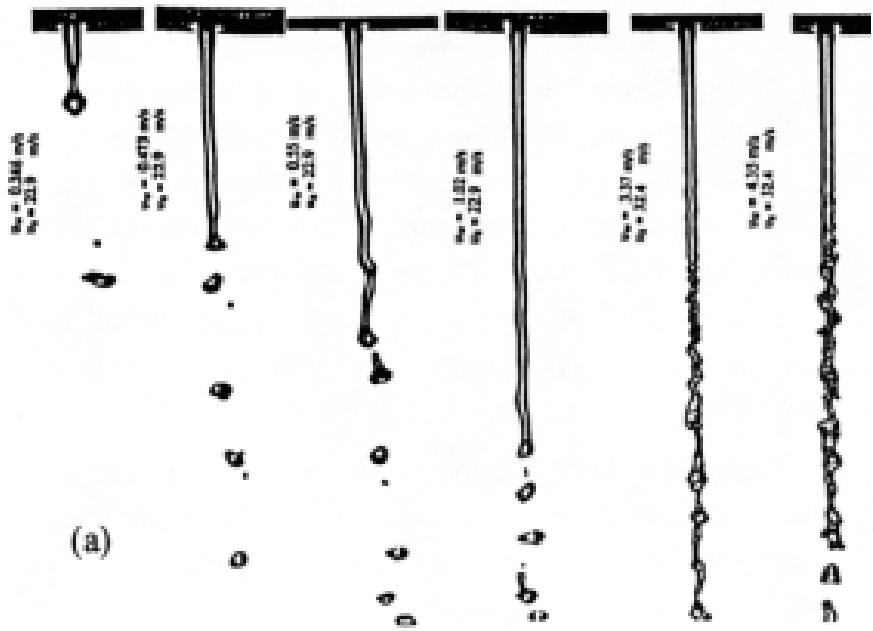
* $We_A = U_L^2 \rho_A d_0 / \sigma$ where ρ_A is the density of gas (air).



$$D = 3.3 \left(\frac{\sigma}{\rho_L g} \right)^{0.5}$$

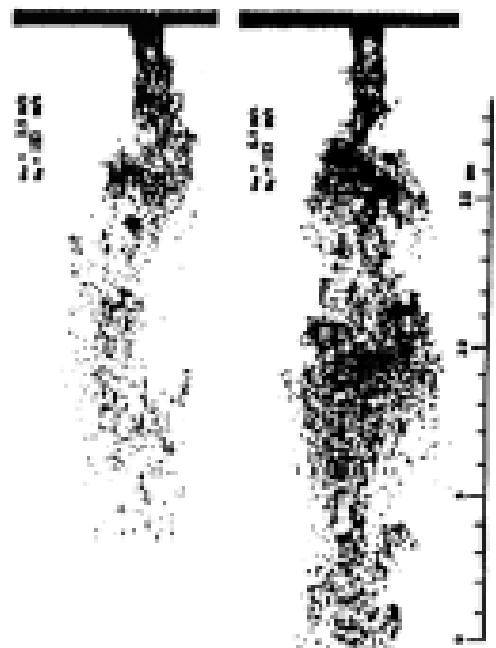
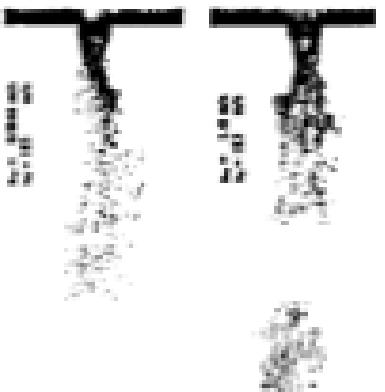
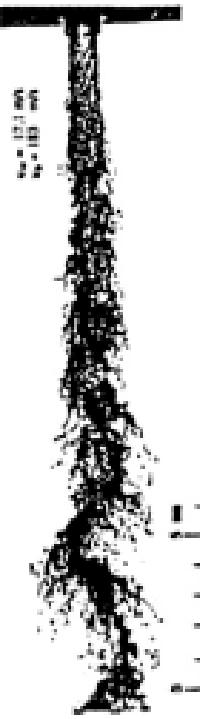
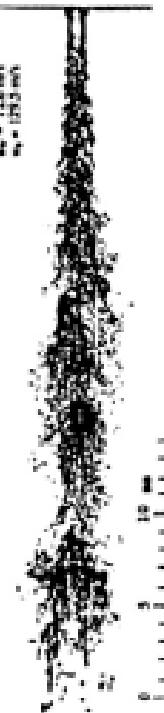
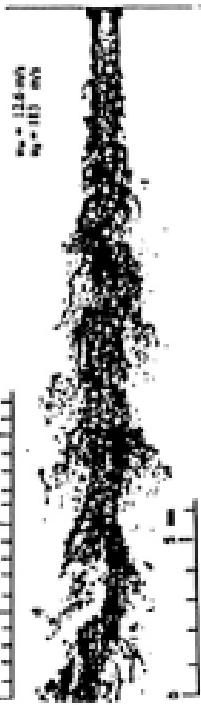
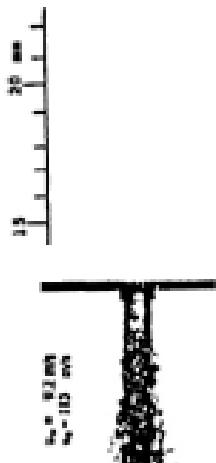
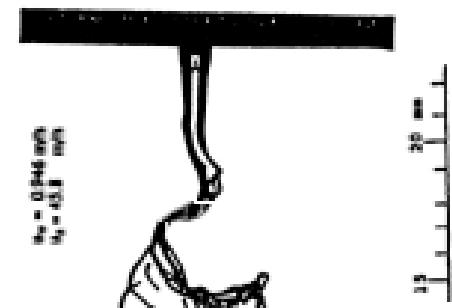
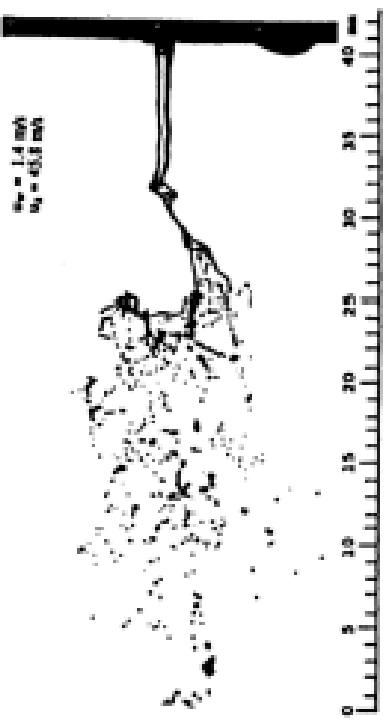
$$Je = \frac{U_L^2 \rho_G d_0}{\sigma} \left(\frac{\rho_L}{\rho_G} \right)^{0.45}$$

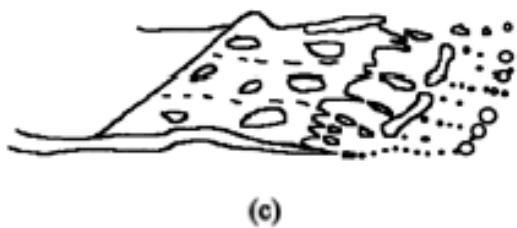
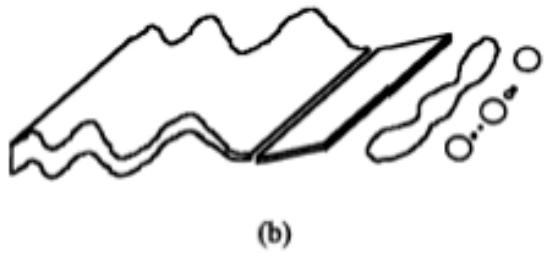
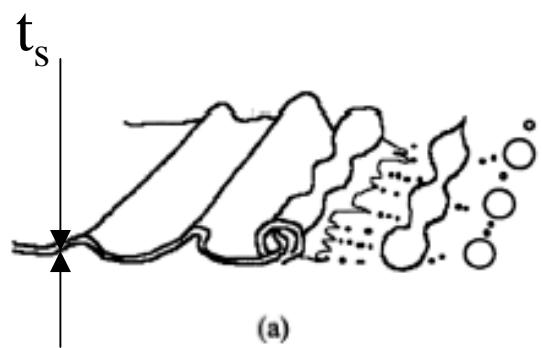
- (a) $Je < 0.1$: Goutte à goutte
- (b) $Je \approx 0.1\text{--}10$: Rupture en gouttes par oscillations longitudinales
- (c) $Je \approx 10\text{--}500$: Rupture par oscillation latérales et frottement aérodynamique
- (d) $Je > 500$: Rupture par formation de membranes ou ligaments



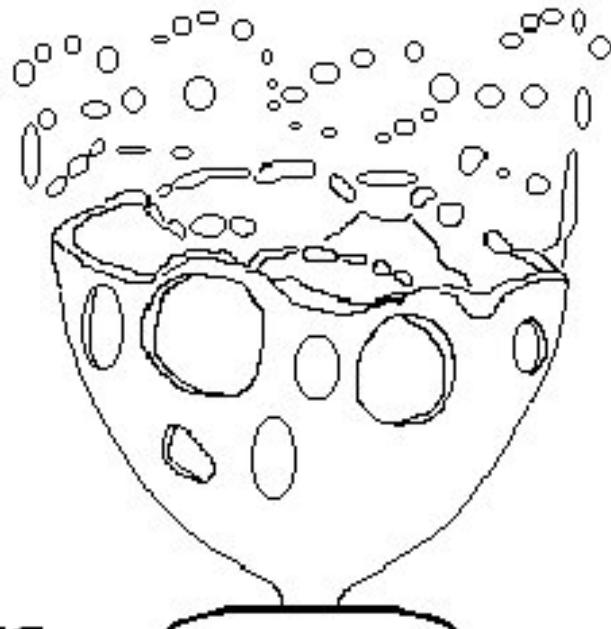
Mechanism of atomization of a liquid jet

R. D. Reitz and F. V. Bracco



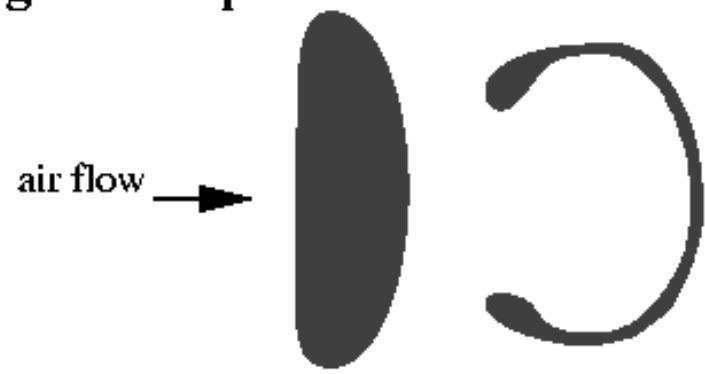


$$\lambda_{opt} = \frac{4\pi\sigma}{\rho_A U_R^2}$$

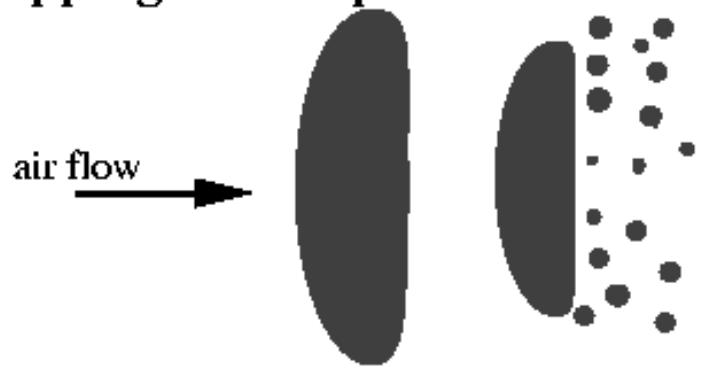


Nappes coniques : $D = 2.13(t_s \lambda_{opt})^{0.5}$

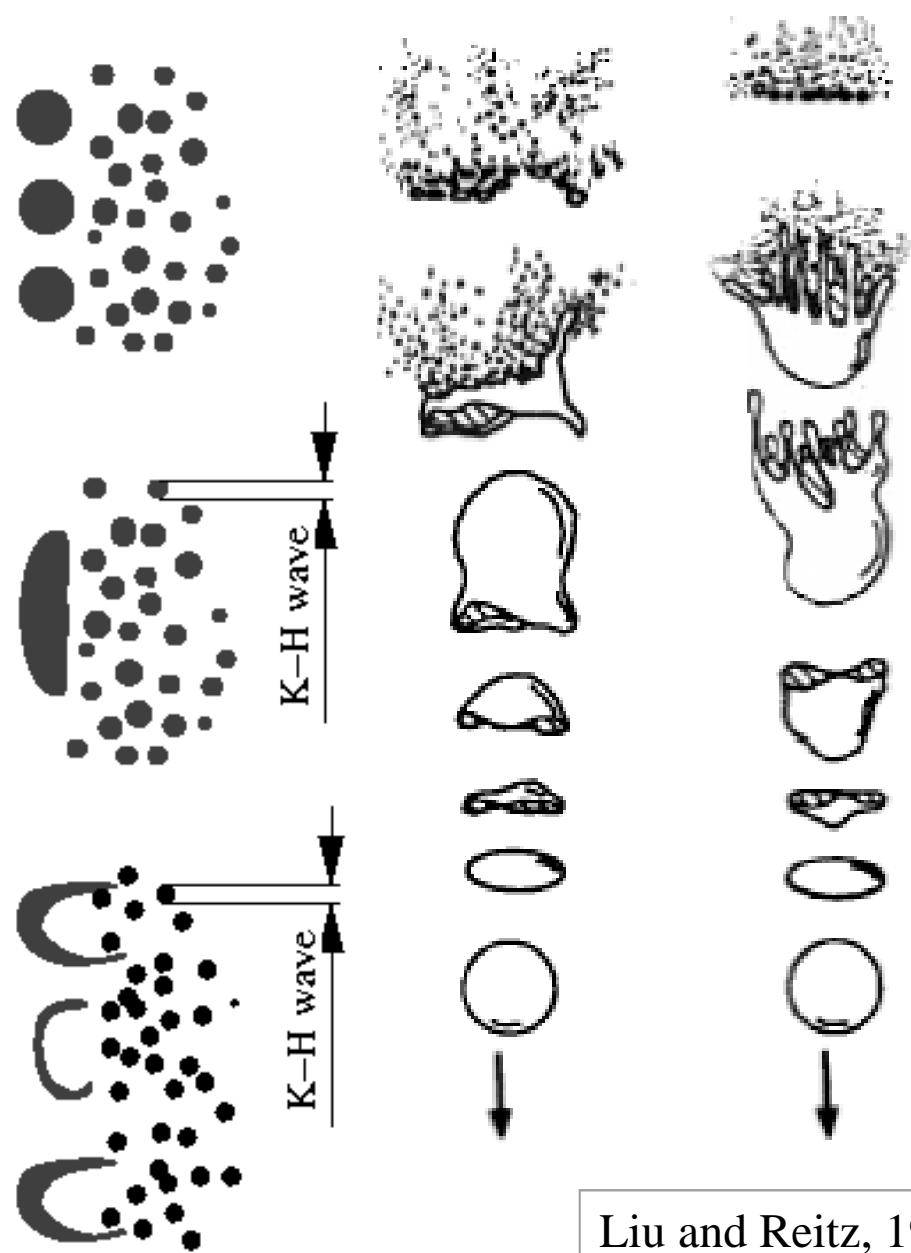
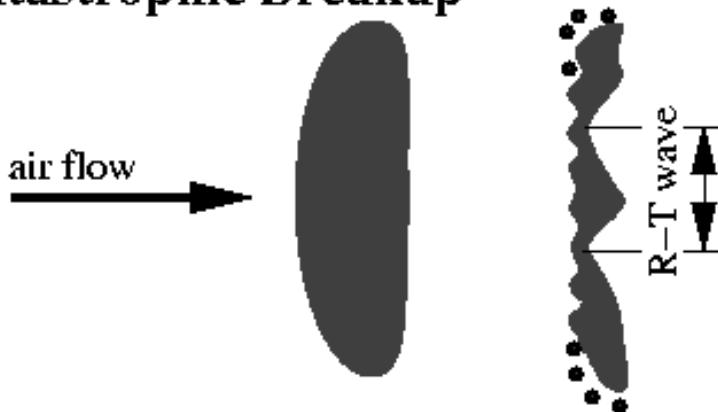
Bag Breakup

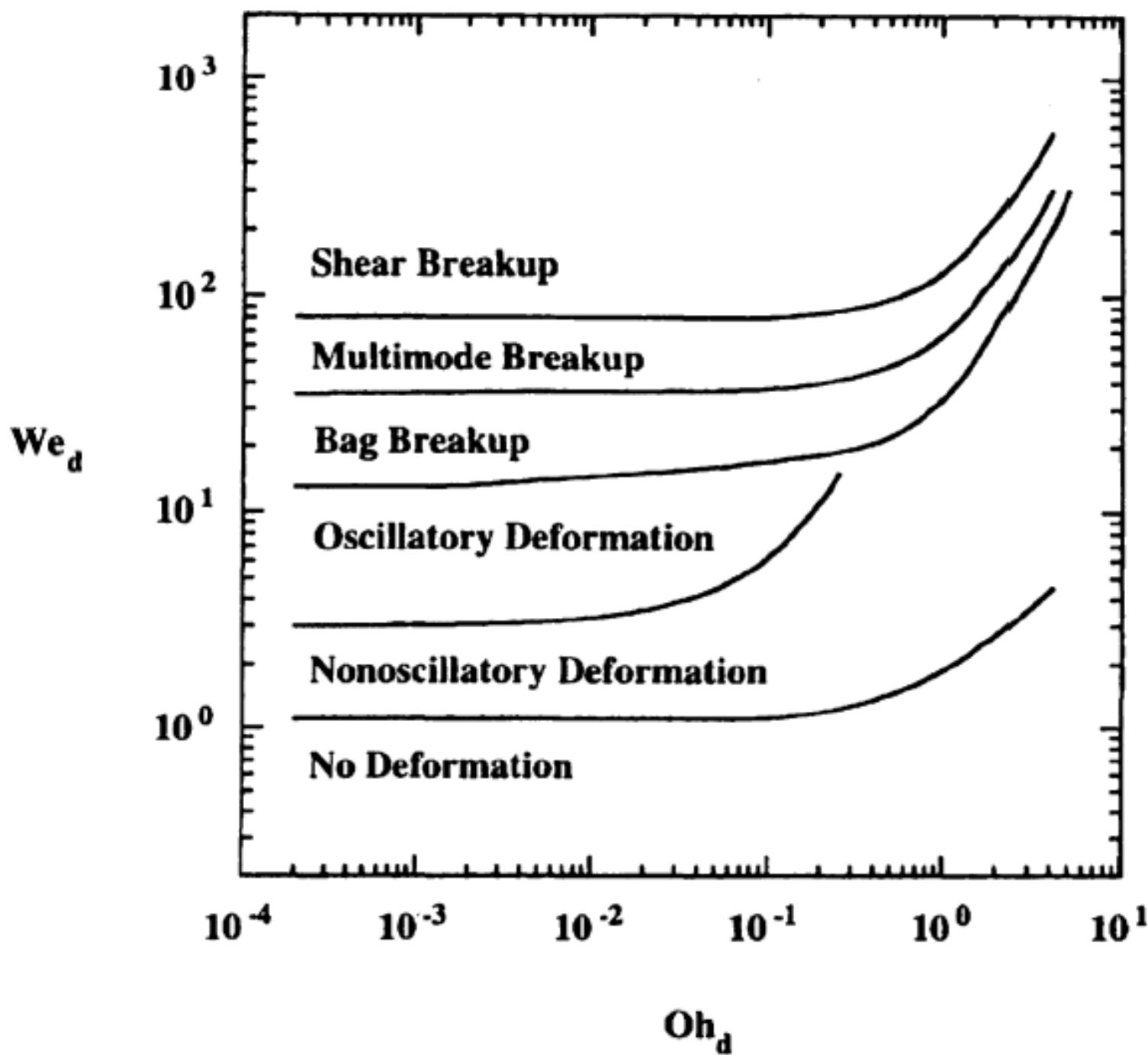


Stripping Breakup



Catastrophic Breakup





$$\frac{\pi D^2}{4} C_D \frac{\rho_A U_R^2}{2} = \pi D \sigma$$

: Équilibre de la goutte
sans effets visqueux

$$We_{crit} = \frac{8}{C_D}$$



$$D_{crit} = \frac{8\sigma}{C_D \rho_A U_R^2}$$

$$U_{R crit} = \left(\frac{8\sigma}{C_D \rho_A D} \right)^{0.5}$$

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

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

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

$$D_{ab} = \left[\frac{\int_{D_{\min}}^{D_{\max}} D^a(dN/dD)dD}{\int_{D_{\min}}^{D_{\max}} D^b(dN/dD)dD} \right]^{1/(a-b)}$$

$$D_{ab} = \left[\frac{\sum N_i D_i^a}{\sum N_i D_i^b} \right]^{1/(a-b)}$$

Quantity	Common Name	a	b	Definition	Application
D_{10}	Arithmetic Mean (Length)	1	0	$\frac{\sum N_i D_i}{\sum N_i}$	Comparison
D_{20}	Surface Mean (Surface Area)	2	0	$\left(\frac{\sum N_i D_i^2}{\sum N_i} \right)^{1/2}$	Surface Area Controlling
D_{30}	Volume Mean (Volume)	3	0	$\left(\frac{\sum N_i D_i^3}{\sum N_i} \right)^{1/3}$	Volume Controlling (Hydrology)
D_{21}	Length Mean (Surface Area-Length)	2	1	$\frac{\sum N_i D_i^2}{\sum N_i D_i}$	Absorption
D_{31}	Length Mean (Volume-Length)	3	1	$\left(\frac{\sum N_i D_i^3}{\sum N_i D_i} \right)^{1/2}$	Evaporation, Molecular Diffusion
D_{32}	Sauter Mean (SMD) (Volume-Surface)	3	2	$\frac{\sum N_i D_i^3}{\sum N_i D_i^2}$	Mass Transfer, Reaction
D_{43}	Herdan Mean (De Brouckere or Herdan) (Weight)	4	3	$\frac{\sum N_i D_i^4}{\sum N_i D_i^3}$	Combustion, Equilibrium

Rupture de jet

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

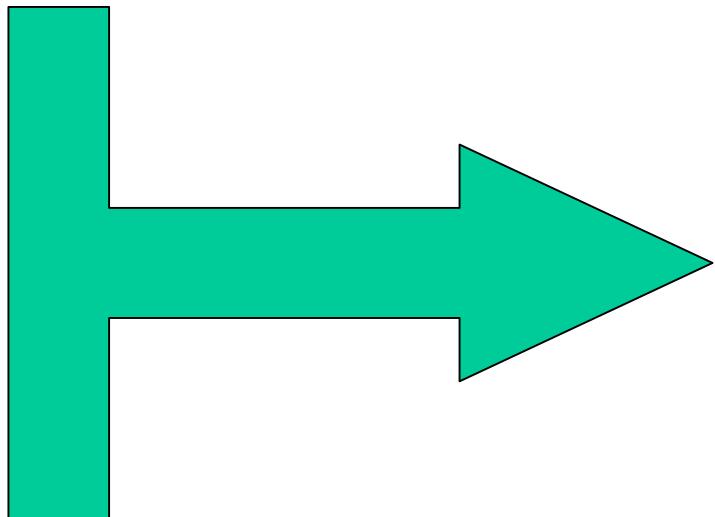
Rupture de cône (swirl atom.)

Correlations	Process Characteristics & Remarks	Refs.
$SMD = 7.3\sigma^{0.6} V_L^{0.2} \dot{m}_L^{0.25} \Delta P_L^{-0.4}$	Very small variations in σ and wide variations in μ_L ; effects of atomizer geometry and air properties not included	Radcliffe [443]
$SMD = 4.4\sigma^{0.6} V_L^{0.16} \dot{m}_L^{0.22} \Delta P_L^{-0.43}$	Effects of atomizer geometry and air properties not included	Jasuja [83]
$SMD = \begin{cases} 133 \frac{FN^{0.64291}}{\Delta P_L^{0.22565} \rho_L^{0.3215}}, & \Delta P_L < 2.8 \text{ MPa} \\ 607 \frac{FN^{0.75344}}{\Delta P_L^{0.19936} \rho_L^{0.3767}}, & \Delta P_L > 2.8 \text{ MPa} \end{cases}$	For kerosene-type fuels; effects of air properties not included	Babu et al. [444]
$SMD = 10^{-3} \sigma (6.11 + 0.32 \times 10^5 FN \rho_L^{0.5} - 6.973 \times 10^{-3} \Delta P_L^{0.5} + 1.89 \times 10^{-6} \Delta P_L)$	Derived from experimental data for 25 different fuels using 6 different simplex nozzles of large Flow numbers; $We_p > 10$; Strong effect of σ , no effect of μ_L ; Discrepant with other data	Kennedy [445]
$MMD = 2.47 \dot{m}_L^{0.315} \Delta P_L^{-0.47} \mu_L^{0.16} \mu_A^{-0.04} \sigma^{0.25} \rho_L^{-0.22} \left(\frac{l_0}{d_0} \right)^{0.03} \left(\frac{l_s}{d_s} \right)^{0.07} \left(\frac{A_p}{d_s d_0} \right)^{-0.13} \left(\frac{d_s}{d_0} \right)^{0.21}$	Derived from experimental data using large-capacity industrial pressure swirl atomizers of large Flow numbers with 50 different geometric configurations. $d_0 \rho_L U_L^2 / \sigma = 11.5 \times 10^3 - 21.55 \times 10^3$, $d_0 \rho_L U_L^3 / \mu_L = 1.913 \times 10^3 - 21.54 \times 10^3$, $\rho_L / \rho_A = 279 - 2235$, $= 694 - 964$	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]
$SMD = 4.52 \left(\frac{\sigma \mu_L^2}{\rho_A \Delta P_L^2} \right)^{0.25} (r_f \cos \theta)^{0.25} + 0.39 \left(\frac{\sigma \rho_L}{\rho_A \Delta P_L} \right)^{0.25} (r_f \cos \theta)^{0.75}$	Effect of spray cone angle considered; film thickness is taken as a primitive variable; it may be estimated from $r_f = 2.7 \left[\frac{d_0 \dot{m}_L \mu_L}{\Delta P_L \rho_L} \right]^{0.25}$	Wang & Lefebvre [449] [448]

Assistance air

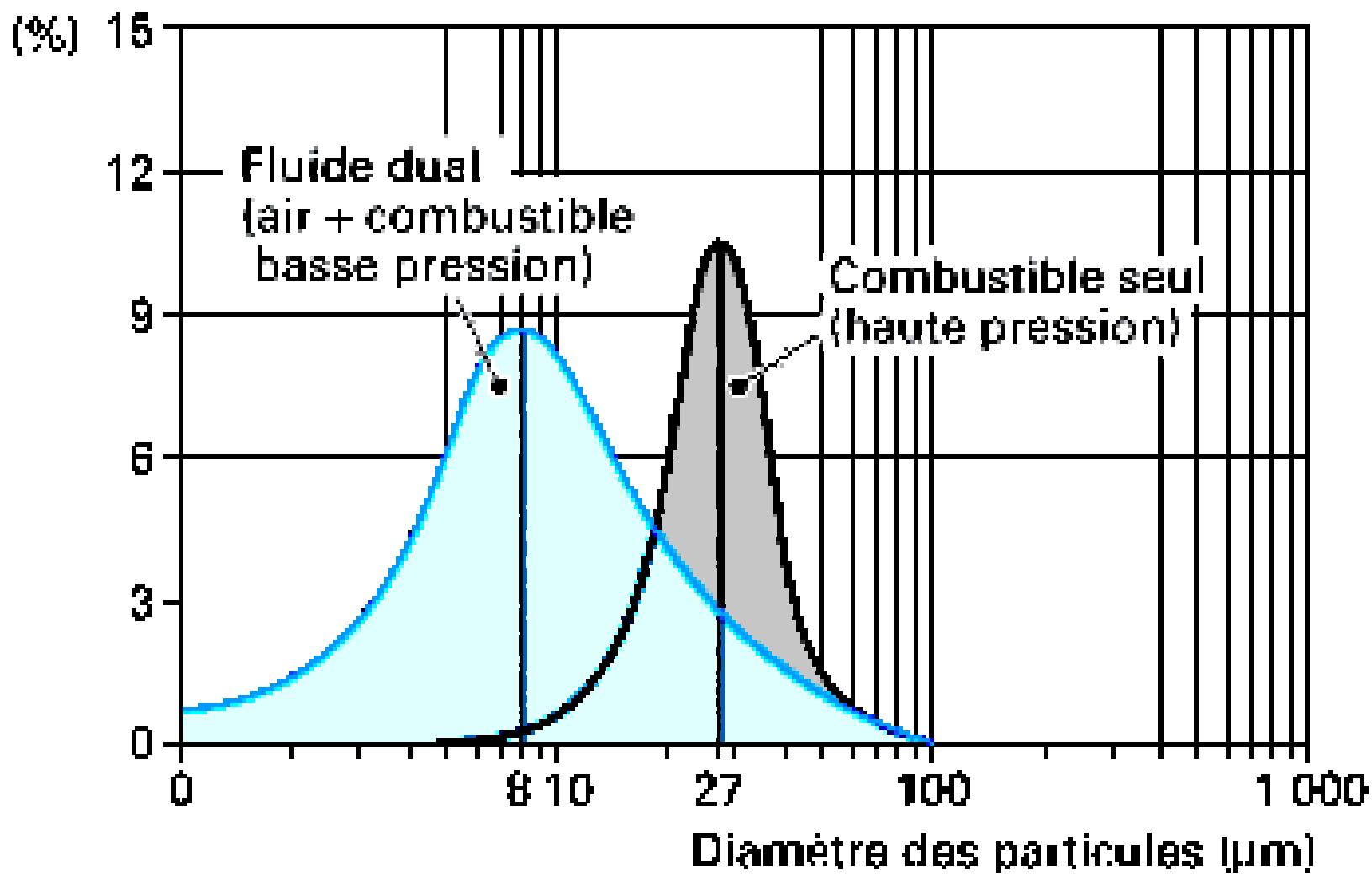
Correlations	Process Characteristics & Remarks	Refs.
$\text{MMD} = 20V_L^{0.5} \dot{m}_L^{0.1} \left(1 + \frac{\dot{m}_L}{\dot{m}_A} \right)^{0.5} \times h^{0.1} \sigma^{0.2} \rho_A^{-0.3} U_R^{-1.0}$ <p>For conditions of droplet coalescence:</p> $\text{MMD}_c = \text{MMD} \left[1 + 5.0 \dot{m}_L^{0.1} \left(\frac{\dot{m}_L}{\dot{m}_A} \right)^{0.6} \right]$	<p><i>Internal mixing air-assist atomizer.</i> Derived from wax spray data in Ref. 461 using NGTE atomizer; Good agreement with fuel-air or fuel-steam spray data;^[163] Discrepant with water-air spray data;^{[79][462]} MMD is to be multiplied by an empirical correction factor for conditions of droplet coalescence.</p>	Wigg ^[75]
$\text{SMD} = 14 \times 10^{-6} d_0^{0.75} \left(\frac{\dot{m}_L}{\dot{m}_A} \right)^{0.75}$	<p><i>Internal-mixing air-assist atomizer.</i> Derived from water-air spray data at $\dot{m}_L = 30-100 \text{ kg/h}$, $\dot{m}_L / \dot{m}_A = 5-100$ using immersion technique</p>	Sakai et al. ^[76]
$\frac{\text{SMD}}{t_{f0}} = \left[1 + \frac{16850 \text{Oh}^{0.5}}{\text{We}(\rho_L / \rho_A)} \right]^{1+} \frac{0.065}{(\dot{m}_A / \dot{m}_L)^2}$ $\text{Oh} = \left(\frac{\mu_L^2}{\rho_L t_{f0} \sigma} \right)^{0.5},$ $\text{We} = \frac{\rho_A t_{f0} U_A^2}{\sigma}$	<p><i>External-mixing air-assist atomizers.</i> 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</p>	Inamura & Nagai ^[77]
$\text{SMD} = 51d_0 \text{Re}^{-0.39} \text{We}^{-0.18} \left(\frac{\dot{m}_L}{\dot{m}_A} \right)^{0.29}$ $\text{Re} = \frac{\rho_L U_R d_0}{\mu_L}, \quad \text{We} = \frac{\rho_L d_0 U_R^2}{\sigma}$	<p><i>External-mixing air-assist atomizers.</i> Derived from kerosene-air spray data with numerous nozzle configurations, including effects of air pressure; Sampled with coated slides</p>	Elkotb et al. ^[78]
$\text{SMD} = C \left(\frac{\rho_L^{0.25} \mu_L^{0.06} \sigma^{0.375}}{\rho_A^{0.375}} \right) \times \left(\frac{\dot{m}_L}{\dot{m}_L U_L + \dot{m}_A U_A} \right)^{0.55}$	<p><i>Pressure and air-assist atomizers.</i> Derived from calibrating fluid (MIL-F-70411)-air spray data using Parker Hannifin spray analyzer</p>	Simmons ^[45]

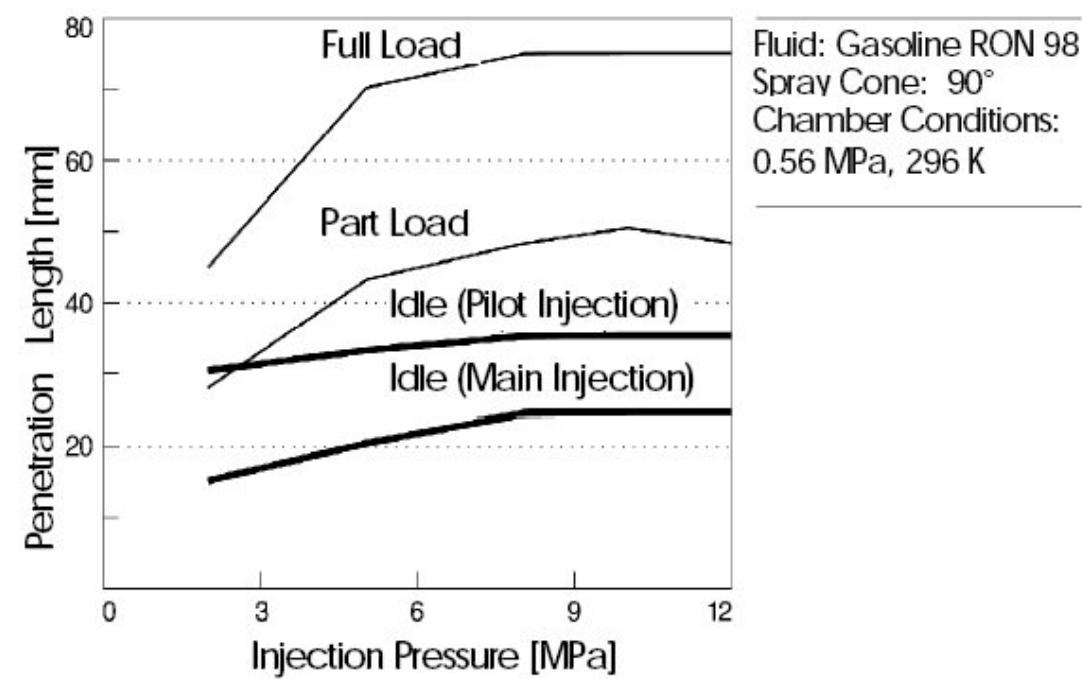
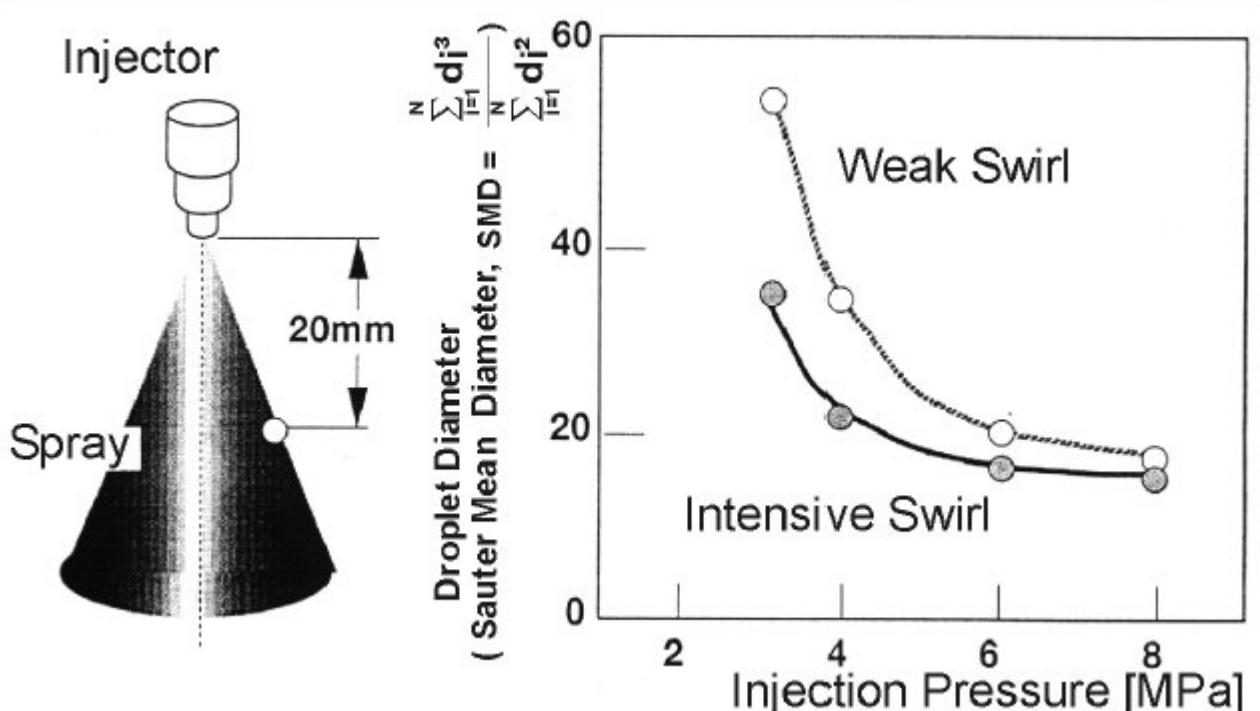
$$E = \sigma \sum_{i=1}^{i=N} \pi \ D_i^2$$

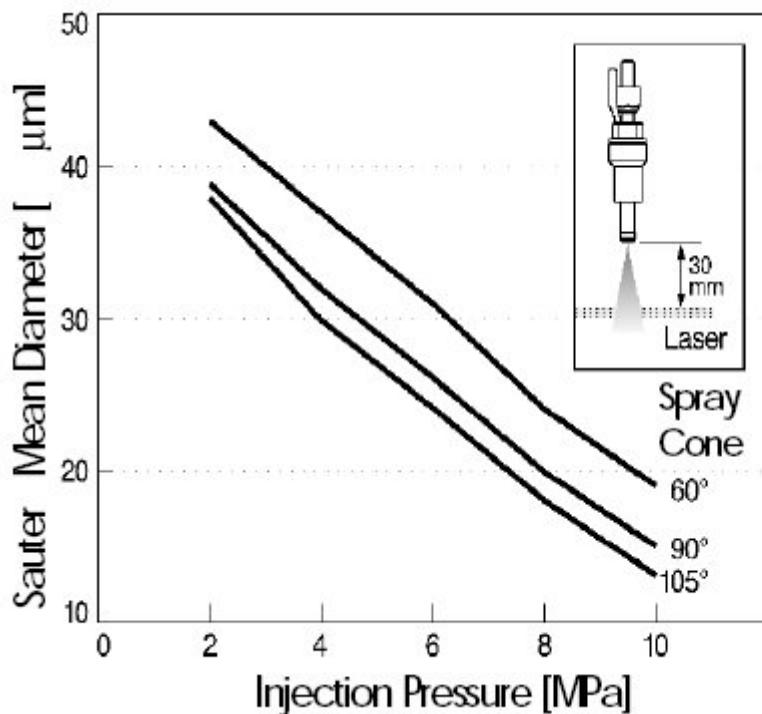


$$E / m_L = \frac{6\sigma}{\rho_L D_{32}}$$

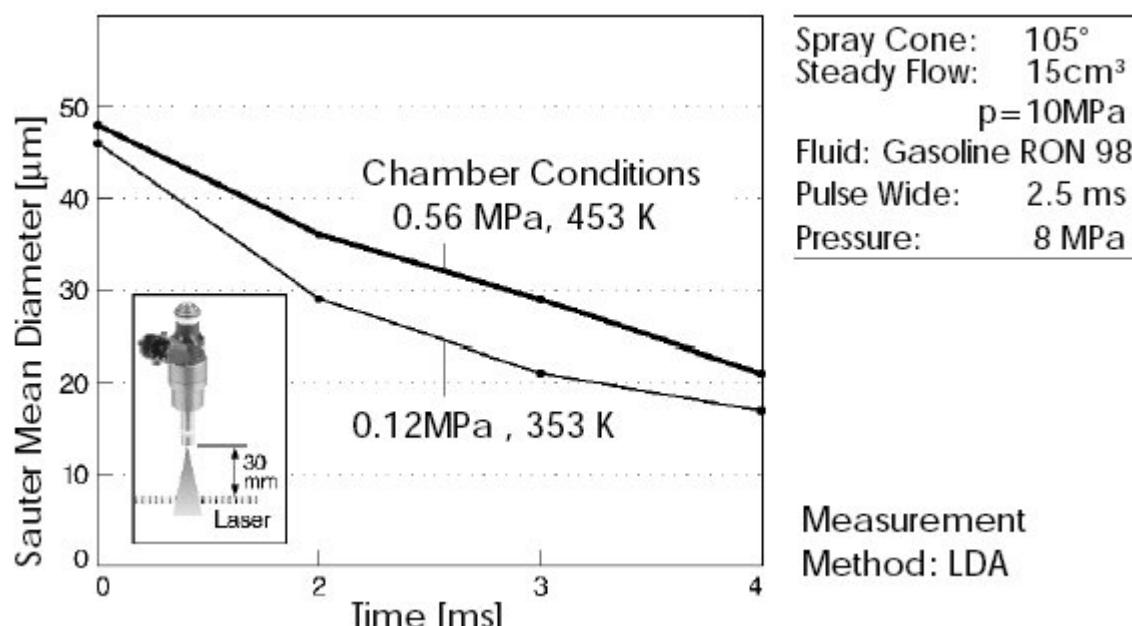
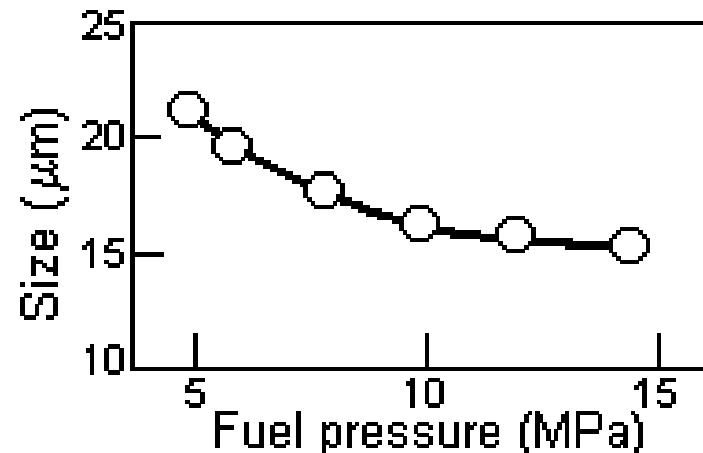
$$m_L = \rho_L \frac{\pi}{6} \sum_{i=1}^{i=N} D_i^3$$



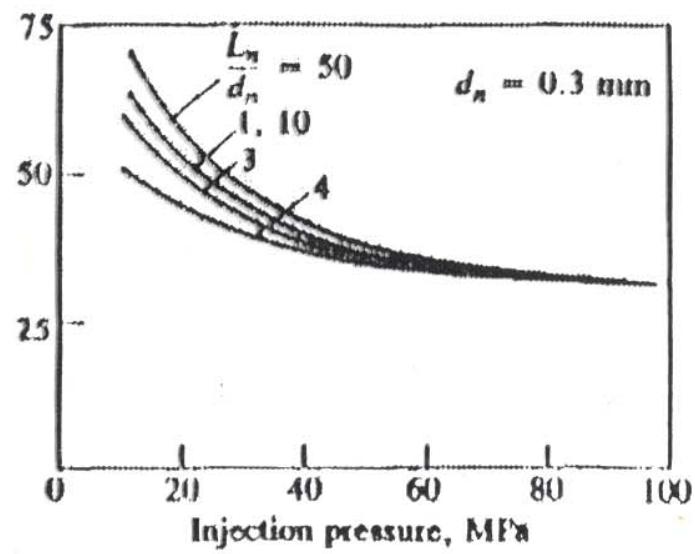




Steady Flow: 15cm³
 p=10MPa
 Fluid: Gasoline RON 98
 Pulse Wide: 2.5 ms
 Injection Against p_{atm}
 Measurement Method: LDA

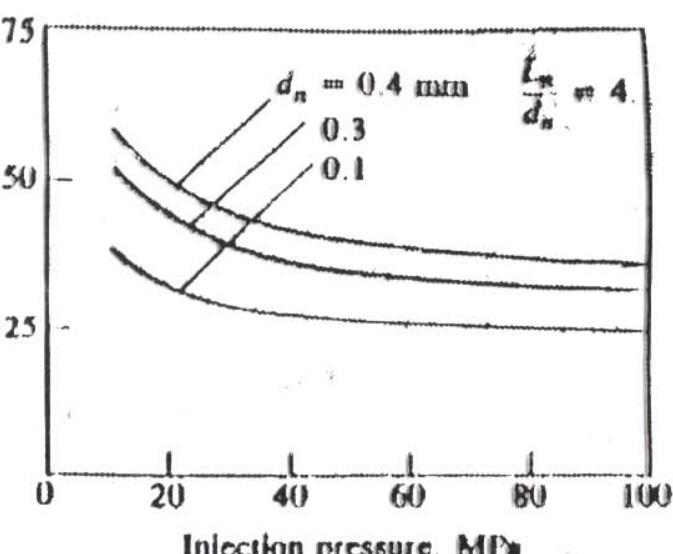


dms

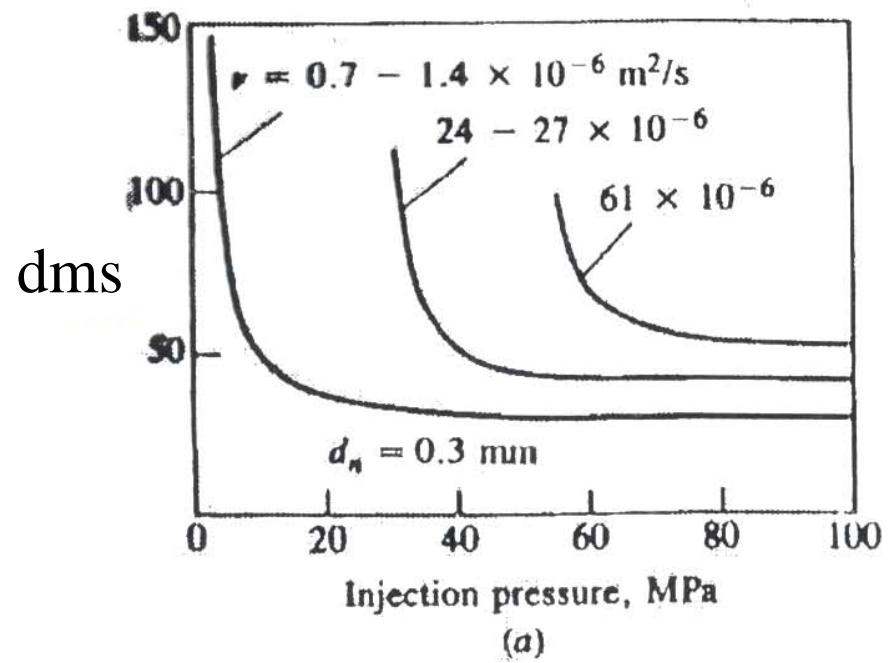


(a)

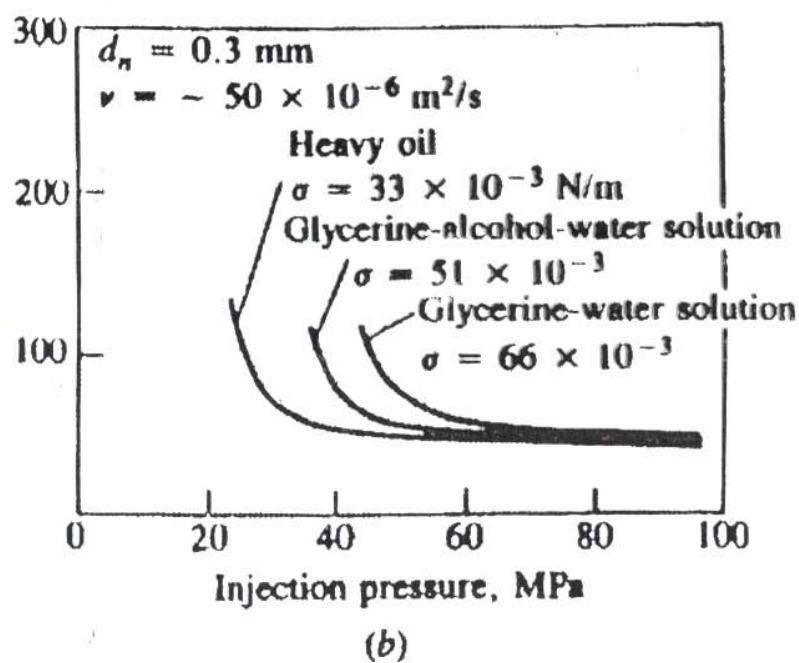
dms



(b)



dms



(b)

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