FOCUSING OF LIQUIDS BY CONVERGENT GAS STREAMS

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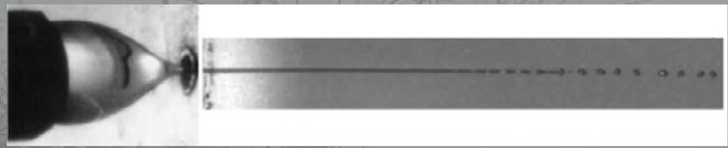
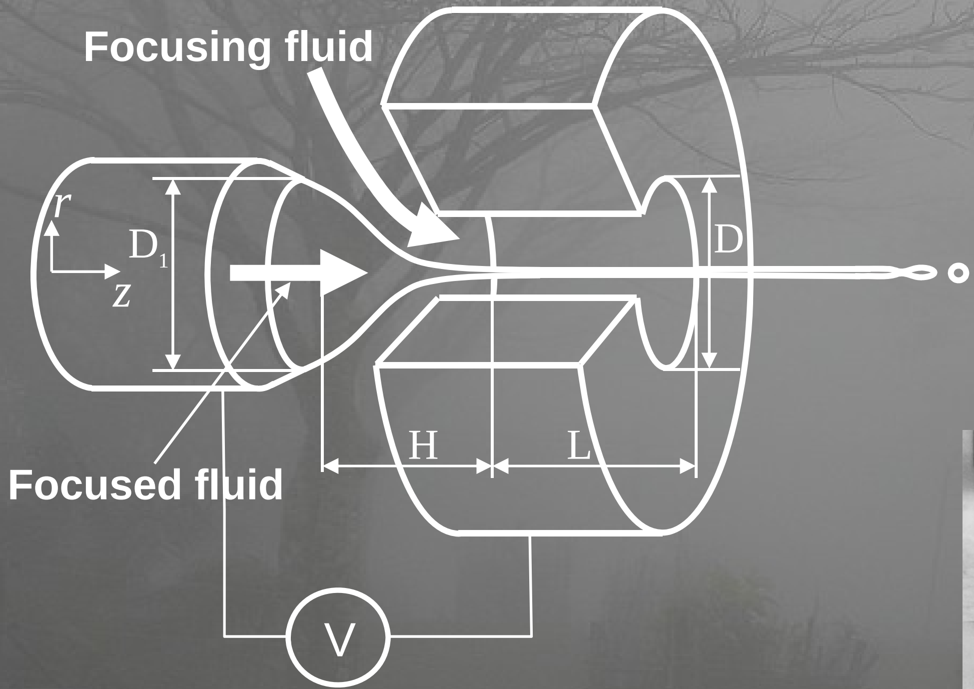
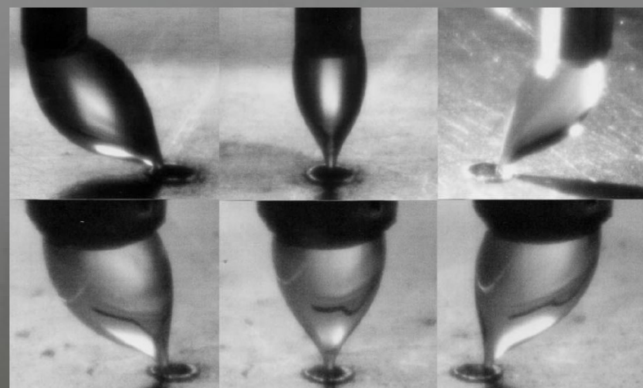
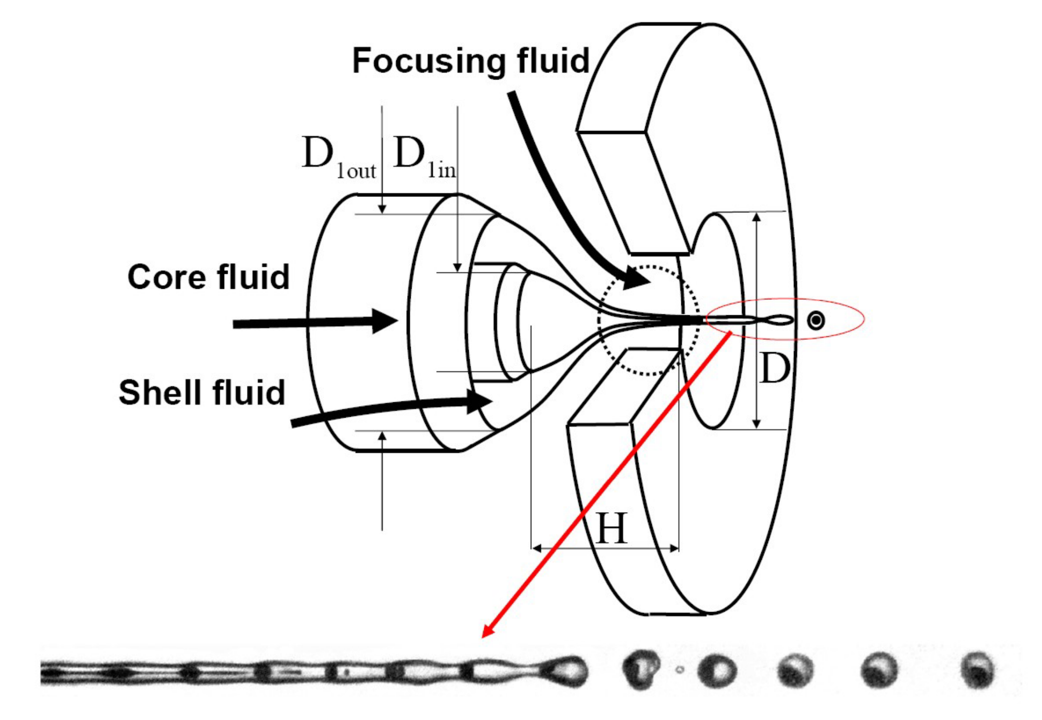
Introduction. Flow Focusing



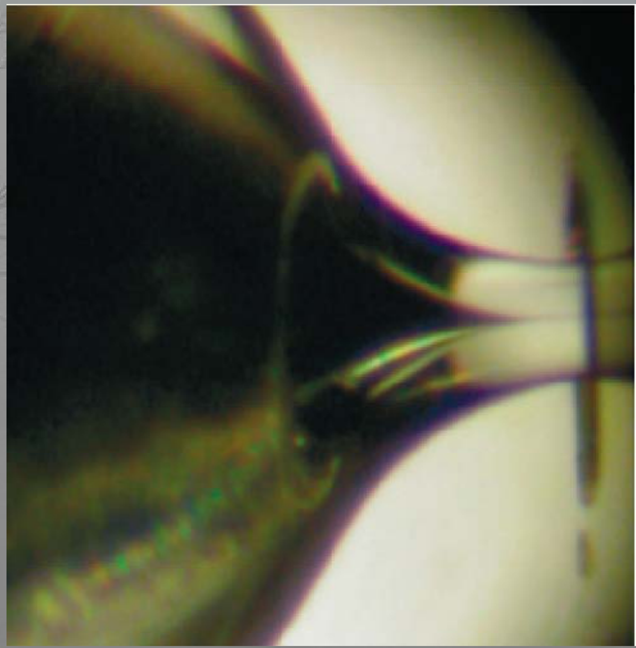




Introduction. Flow Focusing



Gañán-Calvo 1997, W9700034ES



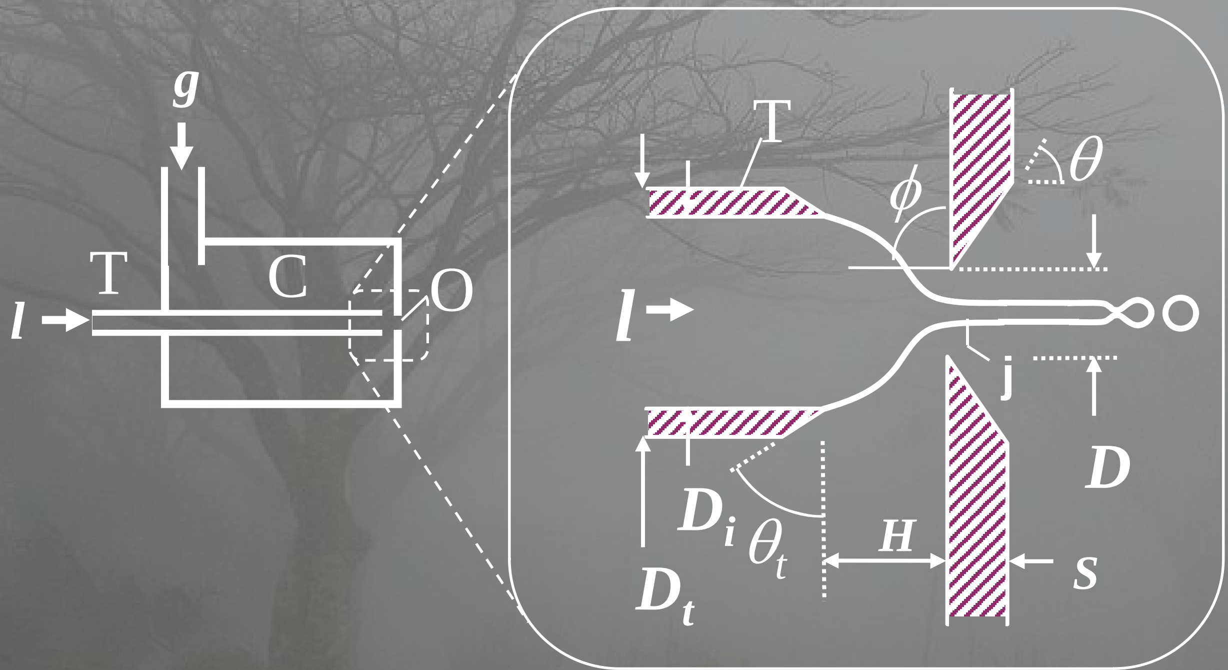
Ganan-Calvo et al. 2007
Nature Phys. 3, 737-742

We may wish to control these structures & make them as small as possible

Motivation

We seek for the geometrical and operational conditions
where the *smallest possible*, *monodisperse* droplets are generated
at a *productivity of practical use*

Geometry

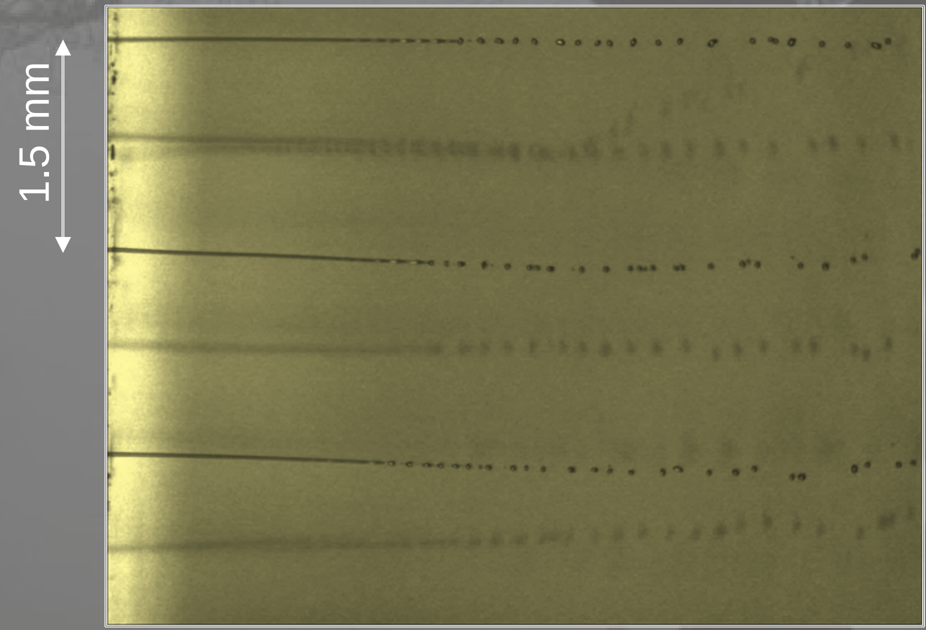


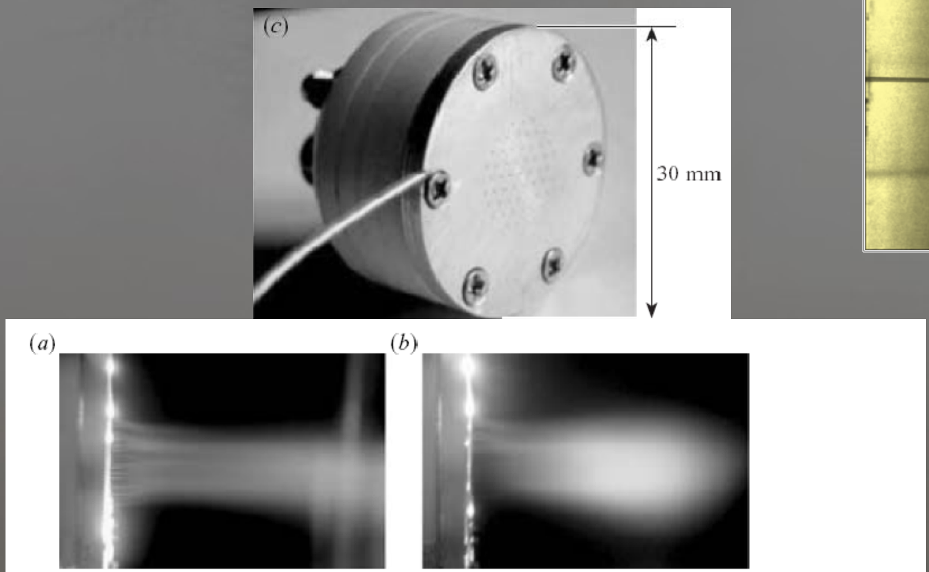
Parameter ranges in experiments (G-C et al.):

	D (μm)	D_i/D	H/D	S (μm)	Θ (^{o})	Θ_t (^{o})
FF	50 - 200	1.5 - 2.5	0.5 - 1.5	50-75	0 and 60	30-to-60
FB	100-700	1	0.15 - 0.3	75-400	60	30-to-60

Geometry
(multiplexing)

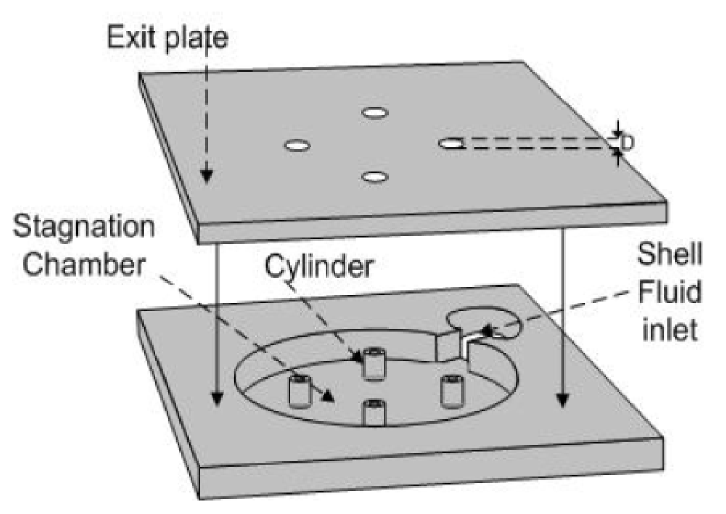
The small yield per orifice has led to the design of multi-orifice devices:



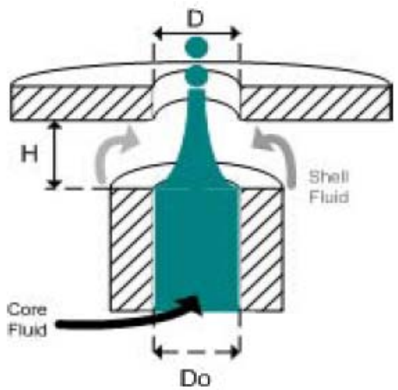


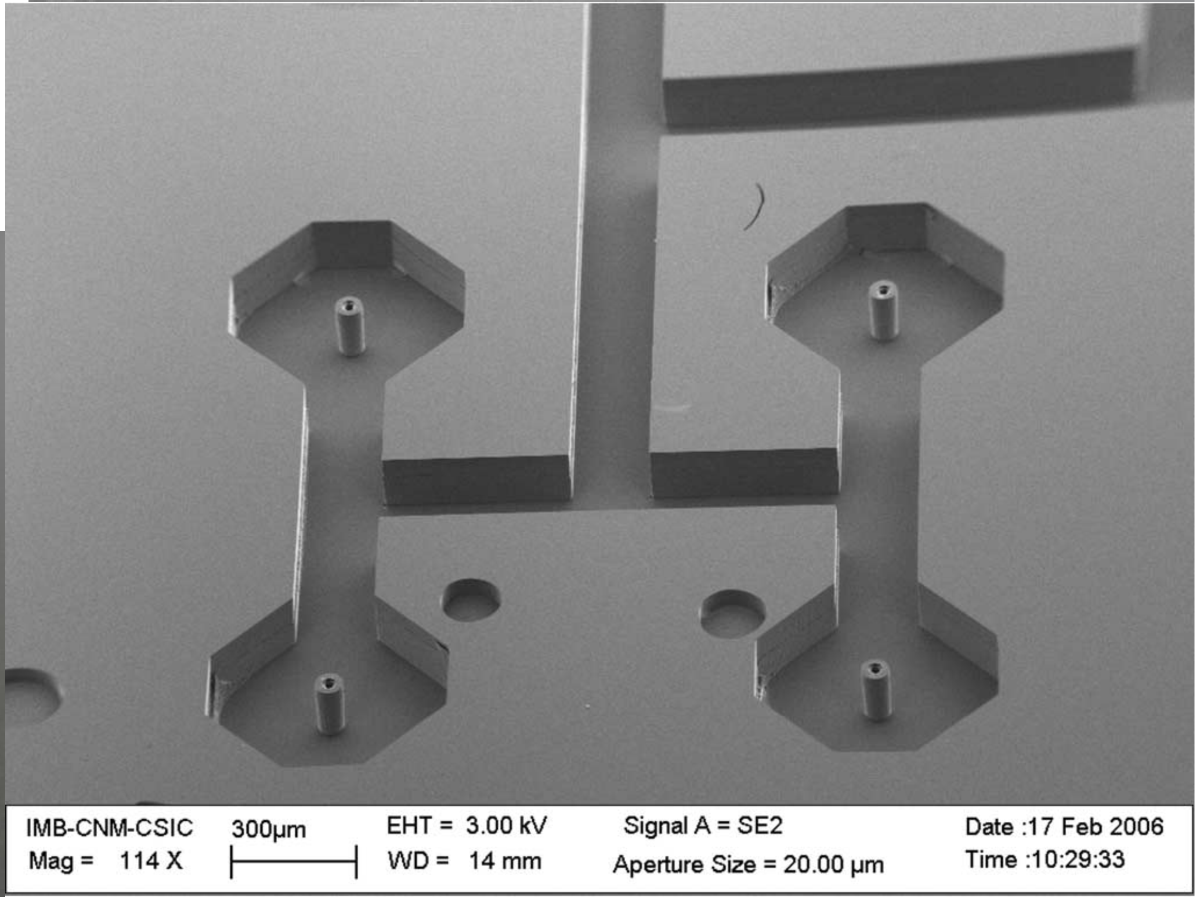
Ethanol spray as issued from device D55 for $Q = 50\,\mathrm{ml\,h^{-1}}$, $\Delta P = 530\,\mathrm{mbar}$, with: (a) 0 V, (b) 1130 V.

Geometry
(multiplexing)



3D (axisymmetric) Flow focusing in silicon





Analysis

- Experimental study
- Analytical solutions
- Linear stability analysis
- Full numerical simulation

Experimental study
Operational conditions

Ranges of pressure drop and flow rate:

	FF	FB
ΔP, bar	0.05 – 30	0.7 – 7.0
Q, uL/min	10 - 5800	10 - 14000

$$\mathrm{Re} >> 1$$

$$\Delta p(Q_{gas}) \approx \frac{1}{2}\rho_l v_l^2 \approx \frac{8\rho_l Q_l^2}{\pi^2 d_j^4} \quad \rightarrow \quad d_j \approx \left(\frac{8\rho_l}{\pi^2 \Delta p}\right)^{1/4} Q_l^{1/2}$$

*A. M. Gañán-Calvo. Phys. Rev. Letter, **80**, 285, 1998.

(Bernoulli)

$$\rightarrow \quad d_o = \left(\frac{8}{\pi^2}\right)^{1/4} \left(\frac{\rho_l Q_l^2}{\Delta p}\right)^{1/4}$$

Characteristic length

Operational conditions

Based on previous characteristic dimension, four main parameters inform on the role played by surface tension, viscosity and geometry (orifice size and tube-orifice distance)

$$\mathrm{We}_l = \left(\frac{\pi^2}{8}\right)^{3/4} \left(\frac{\rho_l Q_l^2 \Delta p^3}{\sigma^4}\right)^{1/4} \geq O(1)$$

$$\mathrm{Re}_l = \left(\frac{2}{\pi^2}\right)^{1/4} \left(\frac{\rho_l^3 Q_l^2 \Delta p}{\mu_l^4}\right)^{1/4}$$

$$G = \left(\frac{8}{\pi^2}\right)^{1/4} \left(\frac{\rho_l Q_l^2}{D^4 \Delta p}\right)^{1/4}$$

$$G_H = H / D$$

Various geometries:

	D (μm)	D_i/D	H/D	S (μm)	Θ (^{o})	Θ_t (^{o})
FF	50 - 200	1.5 - 2.5	0.5 - 1.5	50-75	0 and 60	30-to-60
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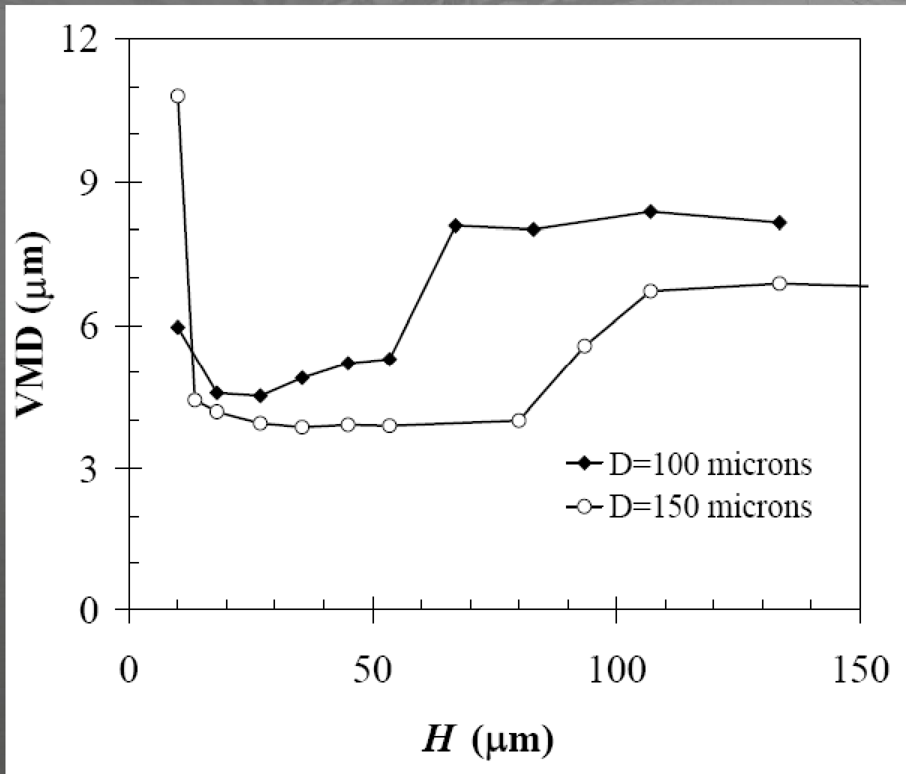
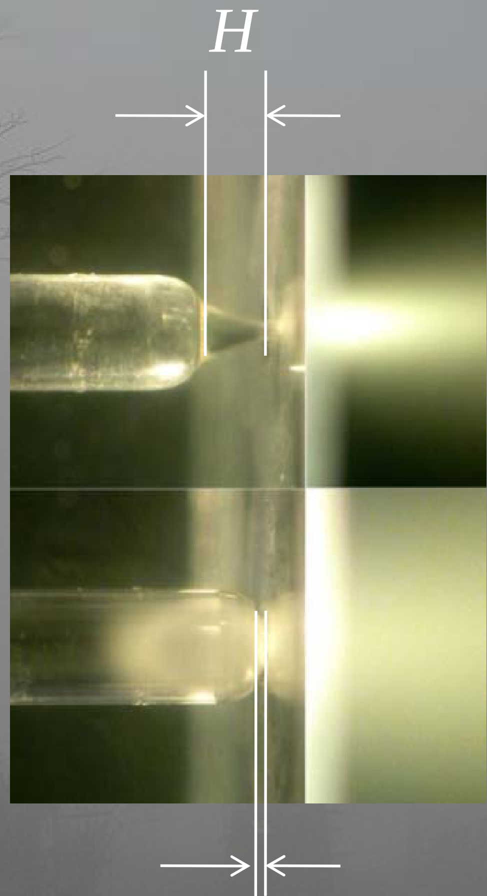
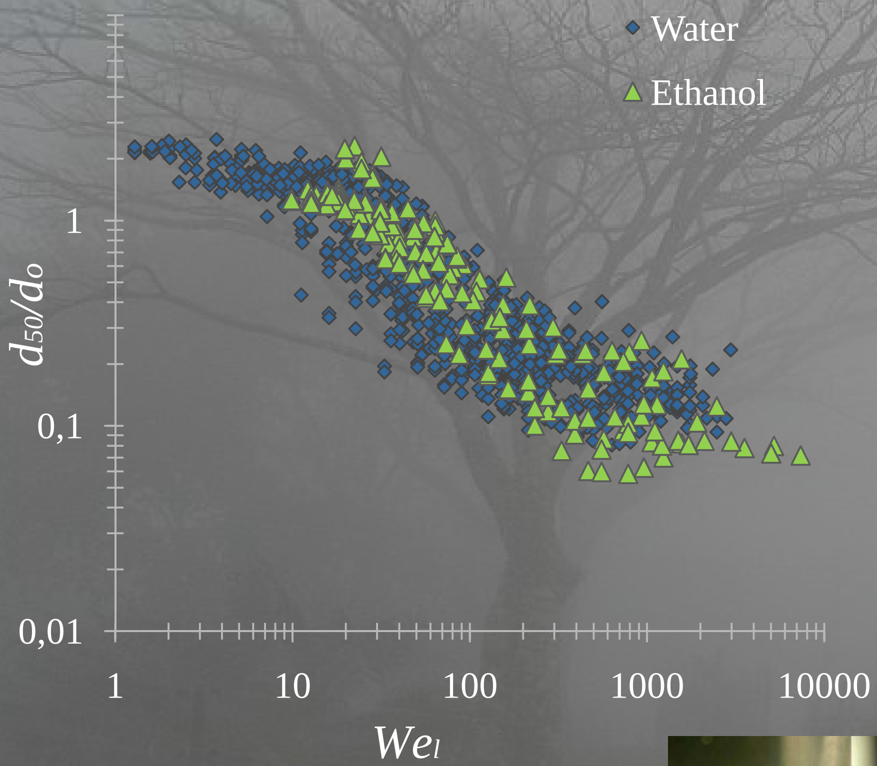
Experimental measurements

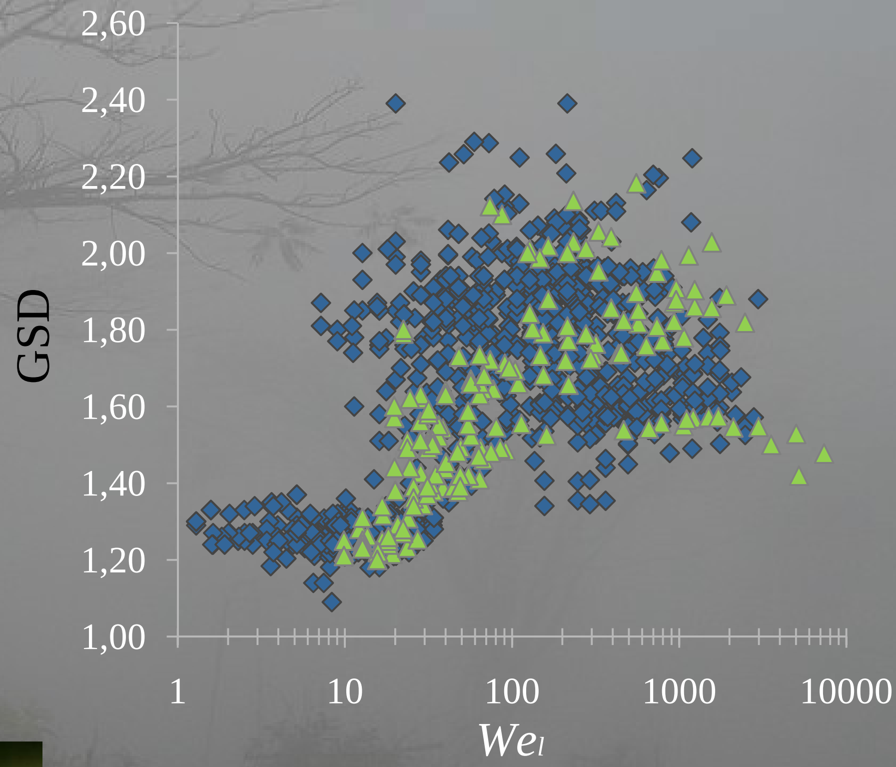
Role played by $G_H = H / D$

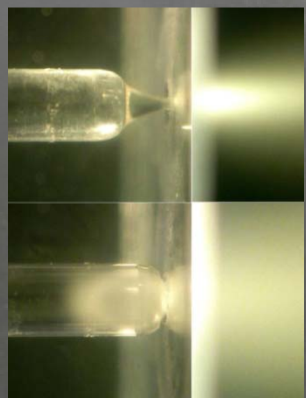




Experimental measurements





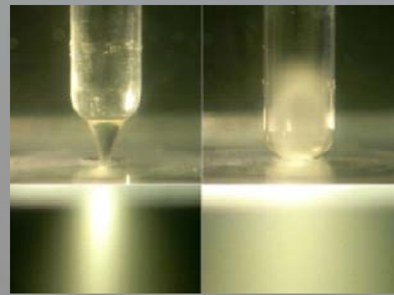


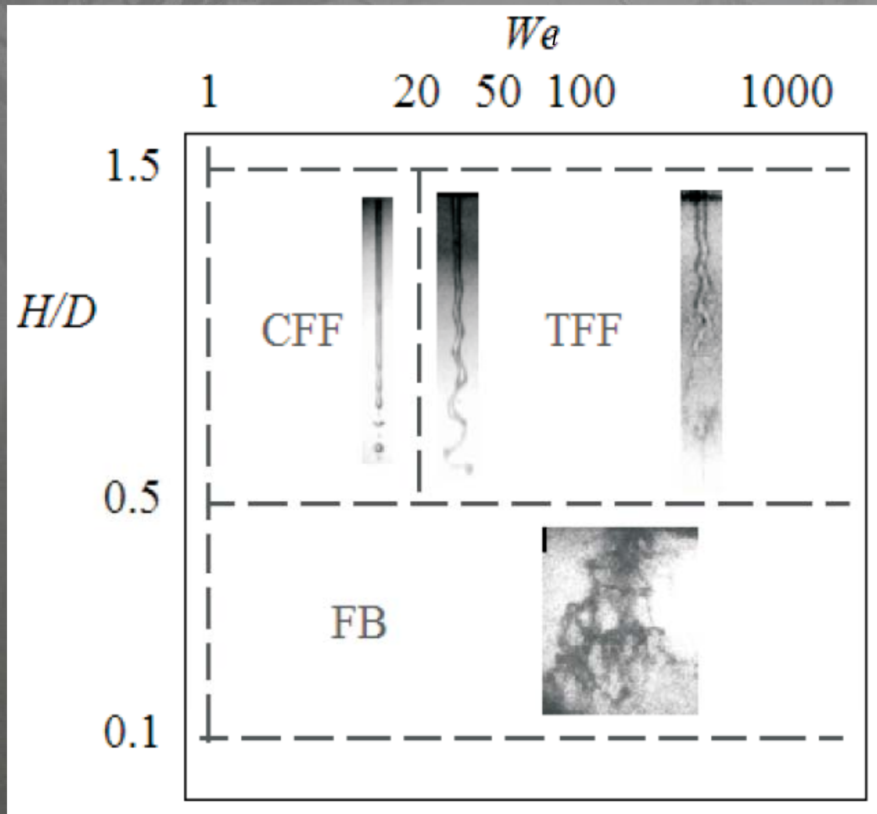
Flow Focusing

Flow Blurring

Experimental measurements

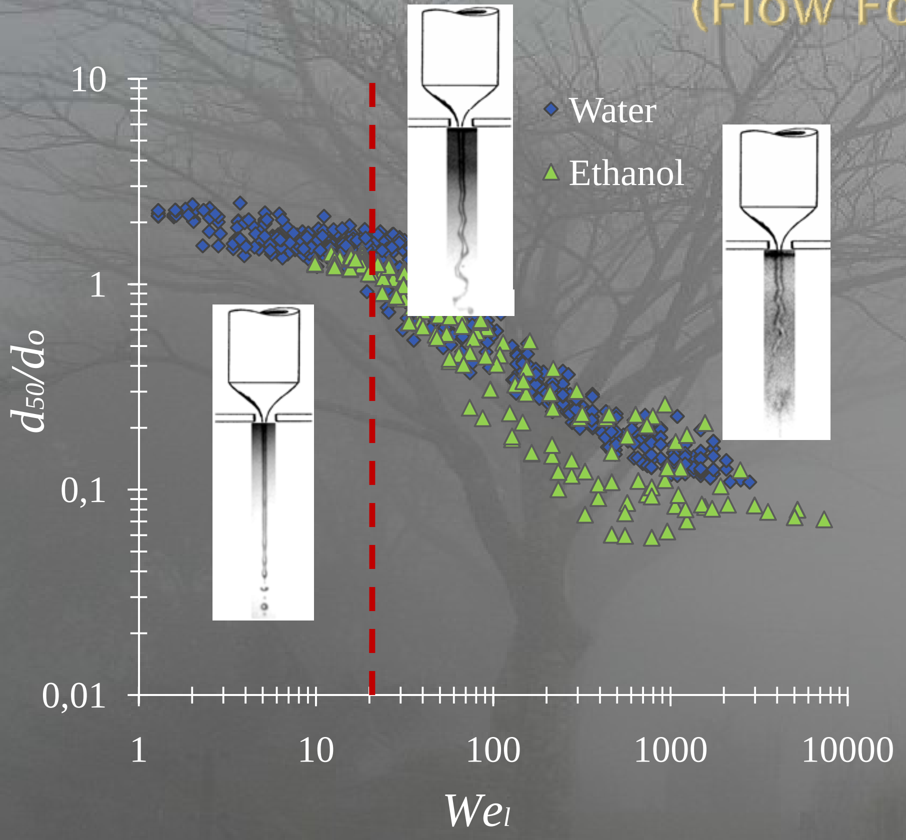
Role played by $G_H = H/L$ and We_l

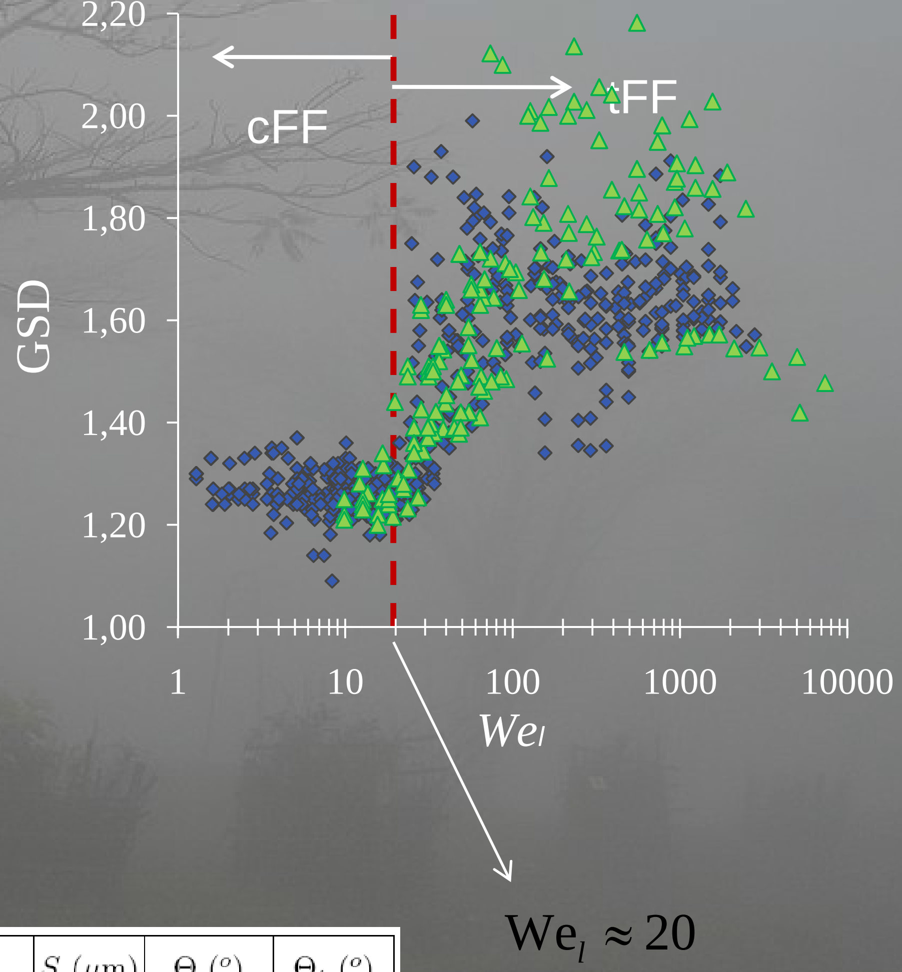




Experimental measurements

(Flow Focusing)

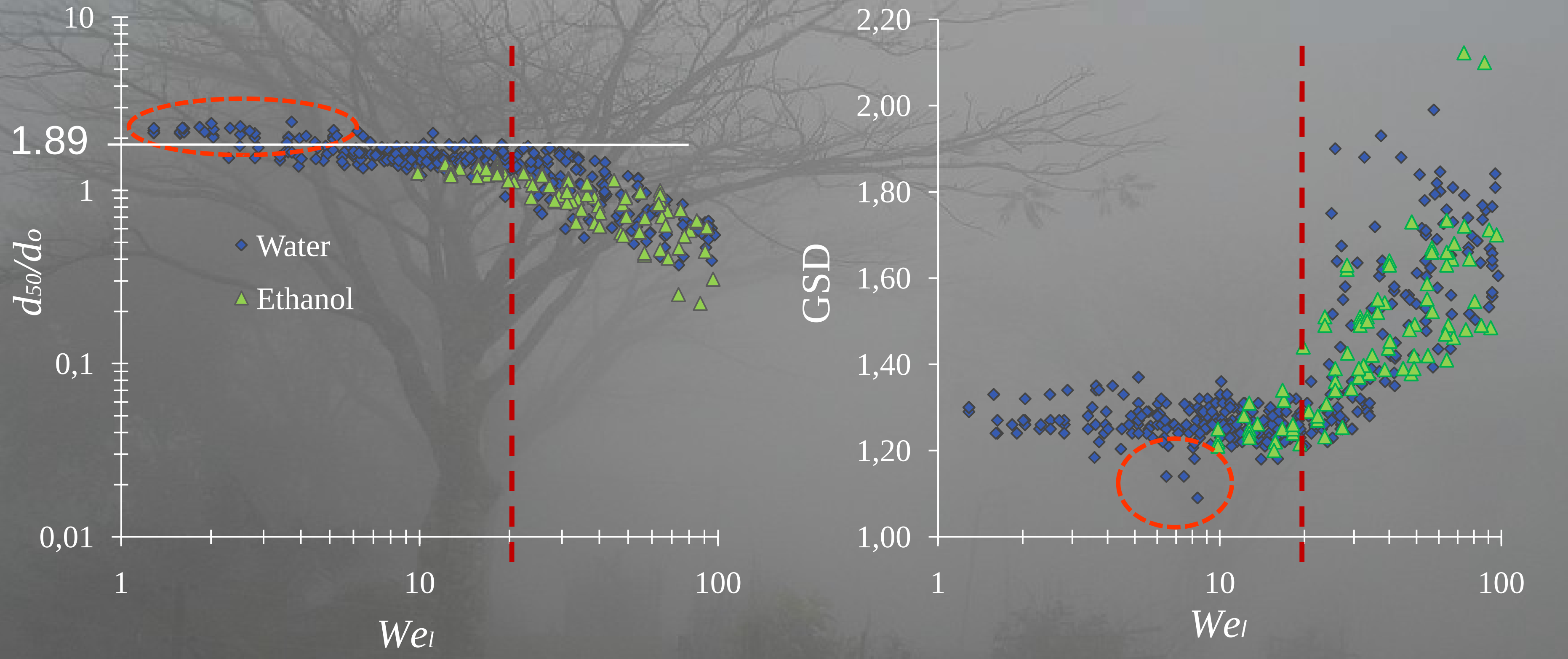




	D (μm)	D_i/D	H/D	S (μm)	Θ (^{o})	Θ_t (^{o})
FF	50 - 200	1.5 - 2.5	0.5 - 1.5	50-75	0 and 60	30-to-60

Experimental measurements

(Flow Focusing)



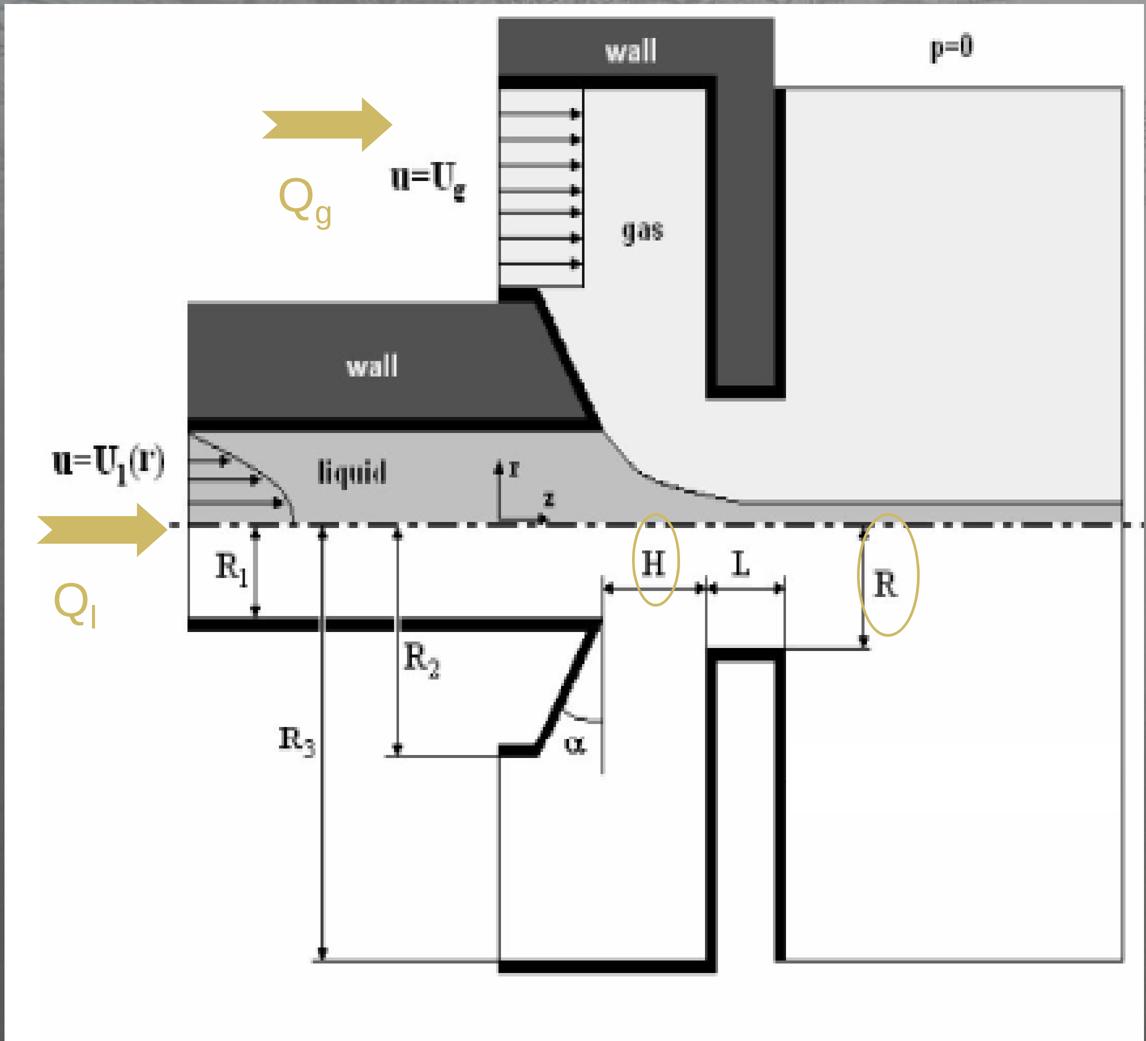
- Why some liquids (water) exhibit larger sizes than predicted, in some (most) conditions?
- Why some conditions exhibit extremely good monodispersity (without external excitation)?
- What exactly sets the minimum flow rate: C/A instability of the jet? Cone-jet flow transition?
- Is the dripping mode so bad?

Full numerical simulation

Some recents FF numerical simulations:

- Liquid-liquid configuration for the production of microemulsions: Michael M. Dupin et al. Physical Review E,73, 2006.
- Microbubbling: M. J. Jensen et al. Physics of Fluids, 18, 2006.

Simulated geometry and flow domains



Geometrical configuration is fixed:

- $R_1/R = 0.75$,
- $R_2/R = 1.75$,
- $R_3/R = 3.5$,
- $L/R = 0.75$.

- $H/R = 1$

Characteristic magnitudes:

* R

* $V = Q_g/(\pi R^2)$

Parameters

$$*\ \alpha = \frac{\rho_g}{\rho_l},\ \text{densities ratio}$$

$$*\ \beta = \frac{\mu_g}{\mu_l},\ \text{viscosities ratio}$$

$$*\ \mathrm{We} = \frac{\rho_g V^2 R}{\sigma},\ \text{Weber (gas)}$$

$$*\ \mathrm{Re} = \frac{\rho_g V R}{\mu_g},\ \text{Reynolds (gas)}$$

$$*\ \mathrm{Re}_R = \frac{\rho_l U_l R}{\mu_l},\ \text{Reynolds (tube)}$$

$$*\ Q = \frac{Q_l}{Q_g},\ \text{Flow rates ratio}$$

Water-air experiments:

$$\alpha = 833.33$$

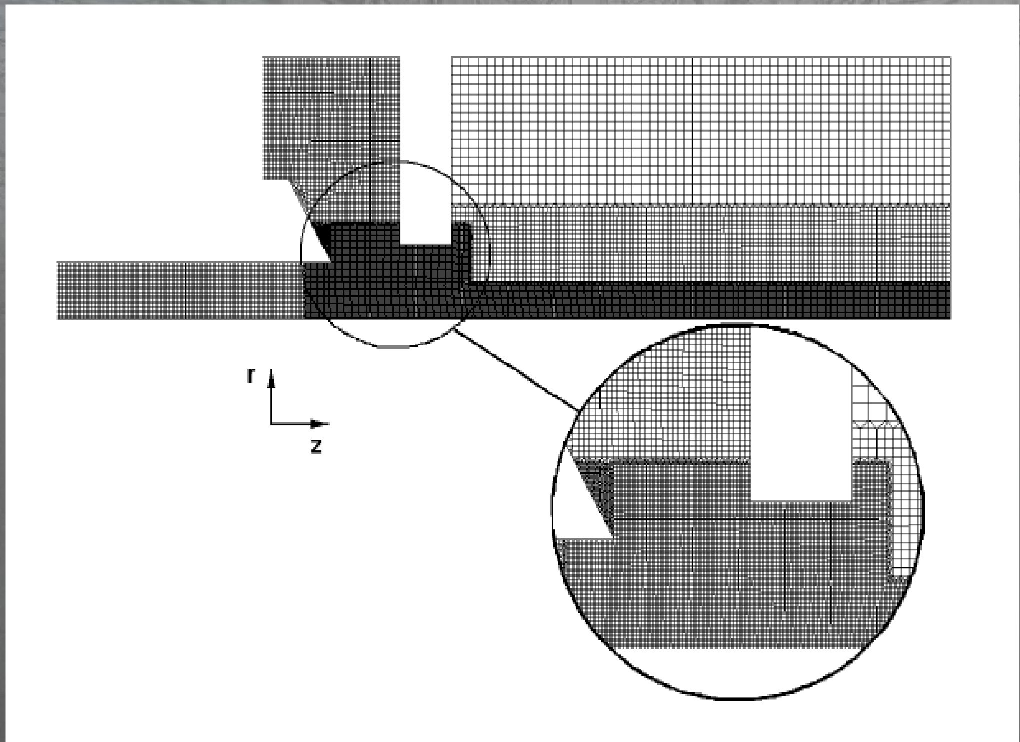
$$\beta = 55.55$$

Case 1	Case 2
Re = 465.8	Re = 931.6
We = 8.13	We = 32.55

In these cases, we have studied the effect of changing *Q* in:

1. Meniscus-jet shape.
2. Minimum flow rate *Q** for stable jet.
3. Flow structure inside the meniscus.

Numerical scheme



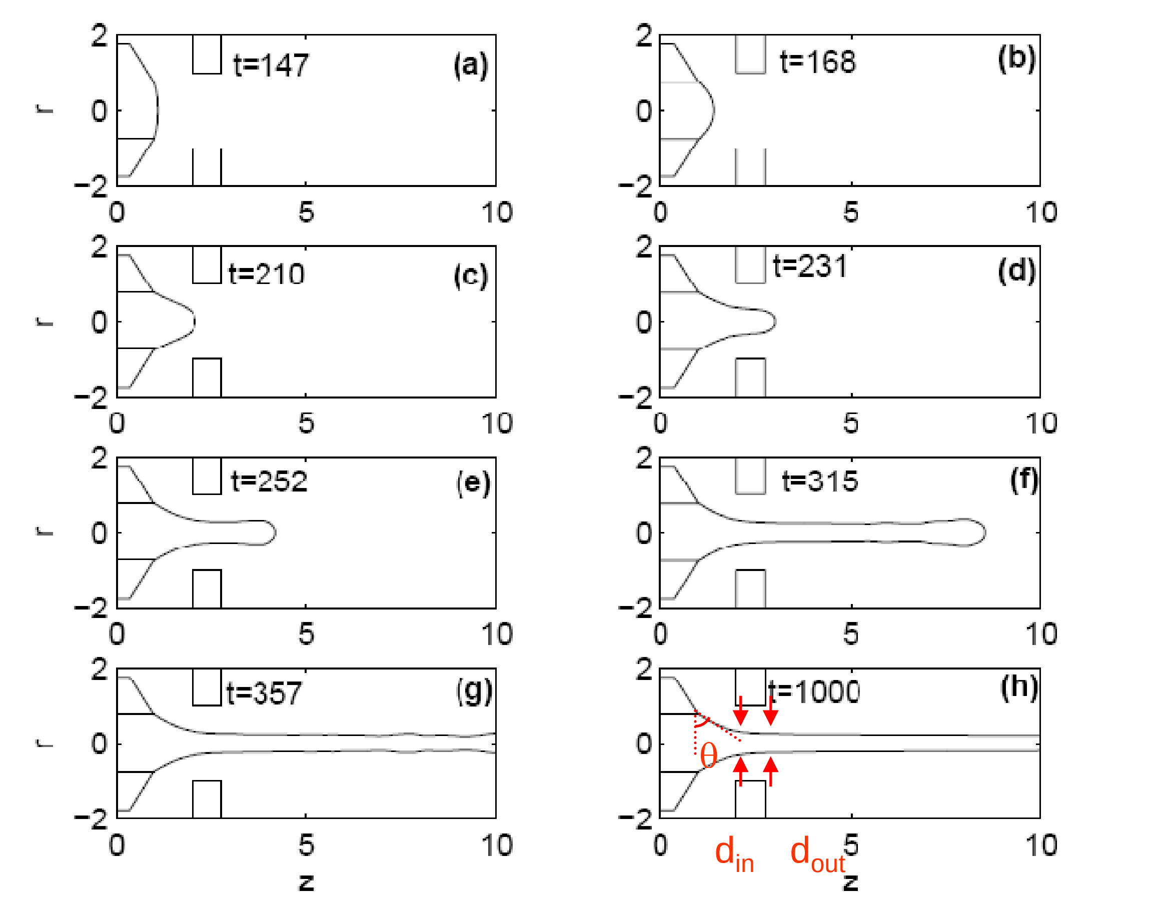
-VOF scheme:

a) Explicit time advance
b) CICSAM reconstruction

*Commercial code used: FLUENT 6.3

Basic mesh: $\Delta_z = \Delta_r = 0.02$
Refined mesh: $\Delta_z = \Delta_r = 0.01$

How a stable jet forms

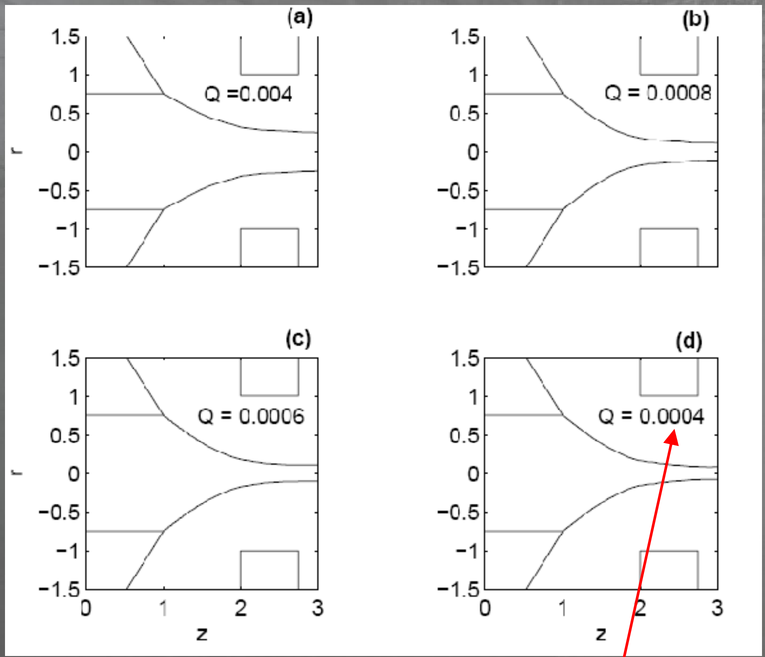


Case 1

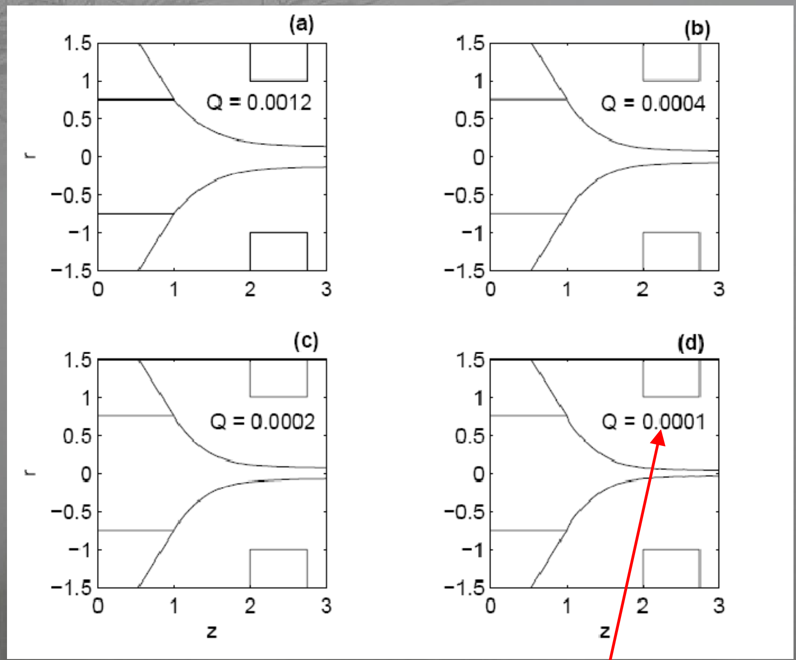
Q=0.004

Meniscus-jet shape vs. Q

Case 1



Case 2



Q (minimum)*

Q (minimum)*

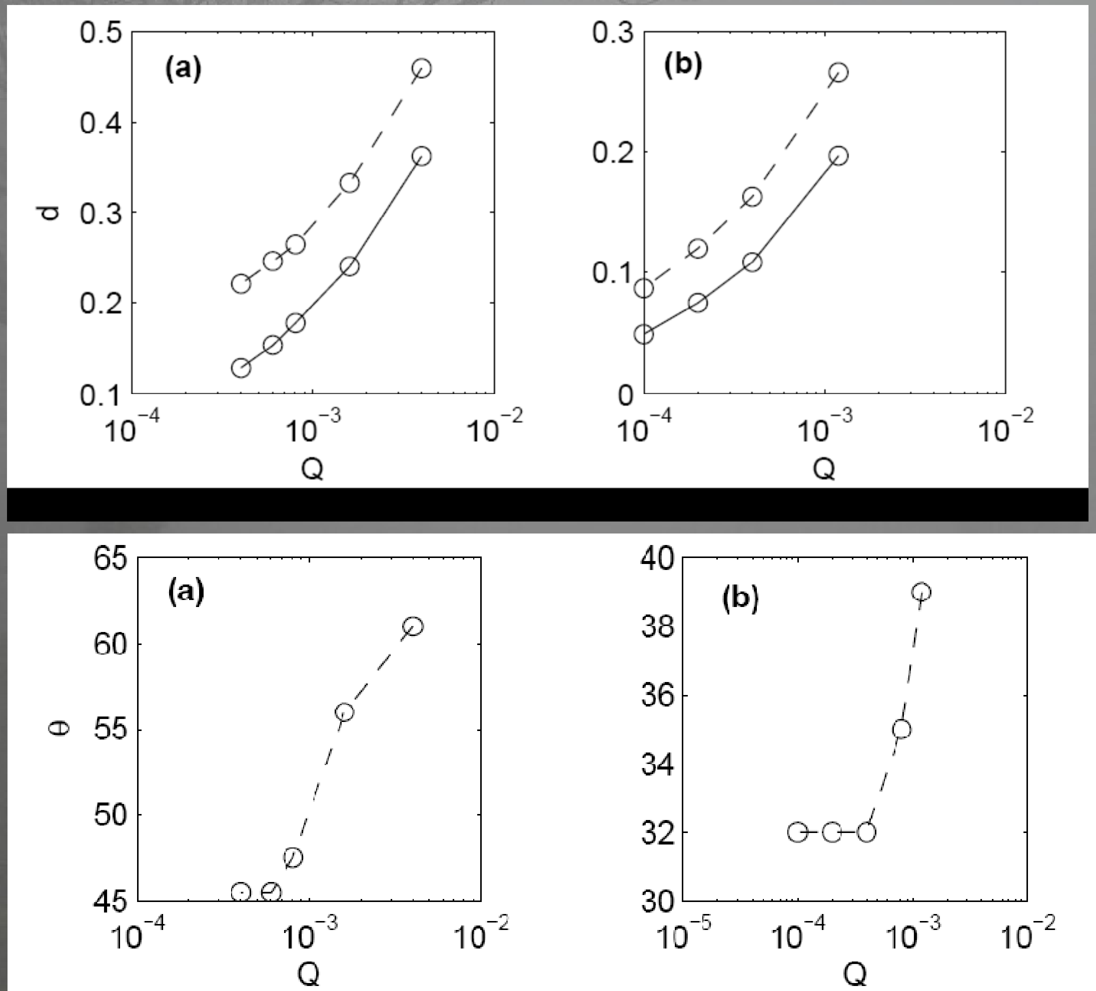
Diameters & contact angles versus Q

Case 1

Case 2

Diameters

"Contact angles"

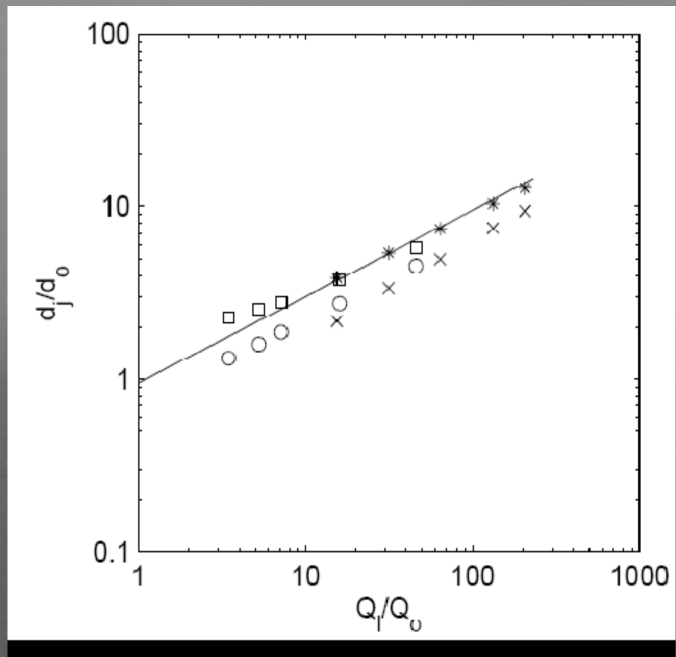


Comparison with scaling laws

$\mathrm{Re} >> 1$

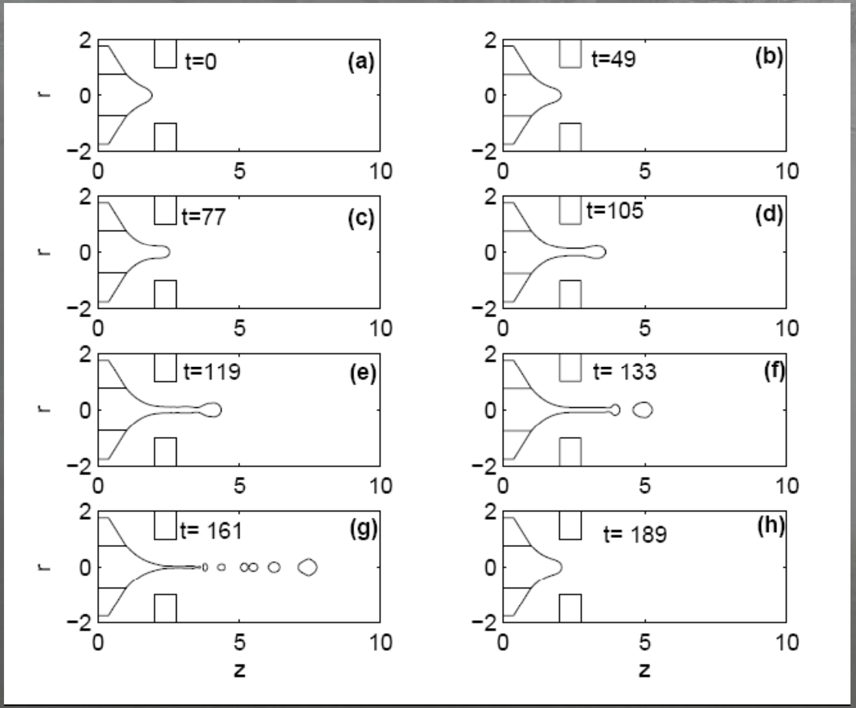
$$\Delta p(Q_{gas}) \approx \frac{1}{2}\rho_l v_l^2 \approx \frac{8\rho_l Q_l^2}{\pi^2 d_j^4} \quad (*)$$

$$d_j \approx \left(\frac{8\rho_l}{\pi^2 \Delta p}\right)^{1/4} Q_l^{1/2}$$



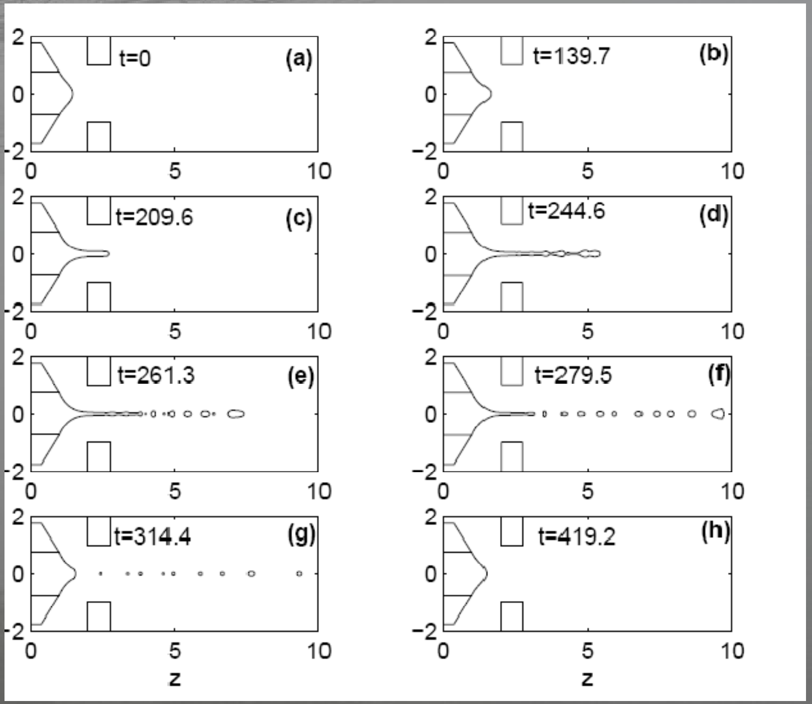
Dripping ($Q<Q^*$)

Case 1



$Q = 0.00024$

Case 2

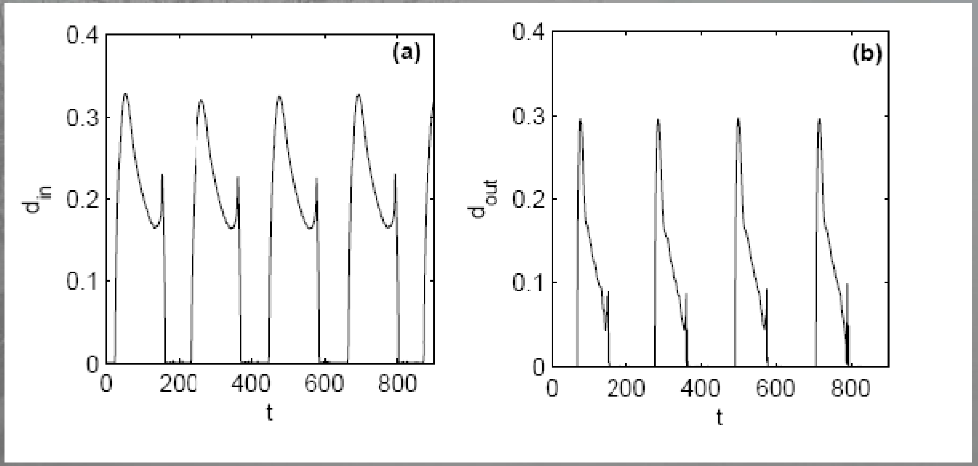


$Q = 0.00004$

Dripping

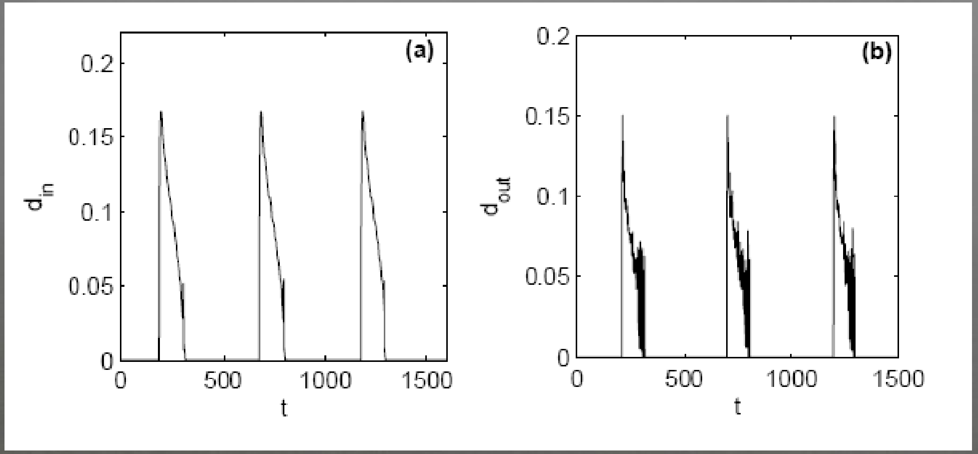
Case 1

Q = 0.00024



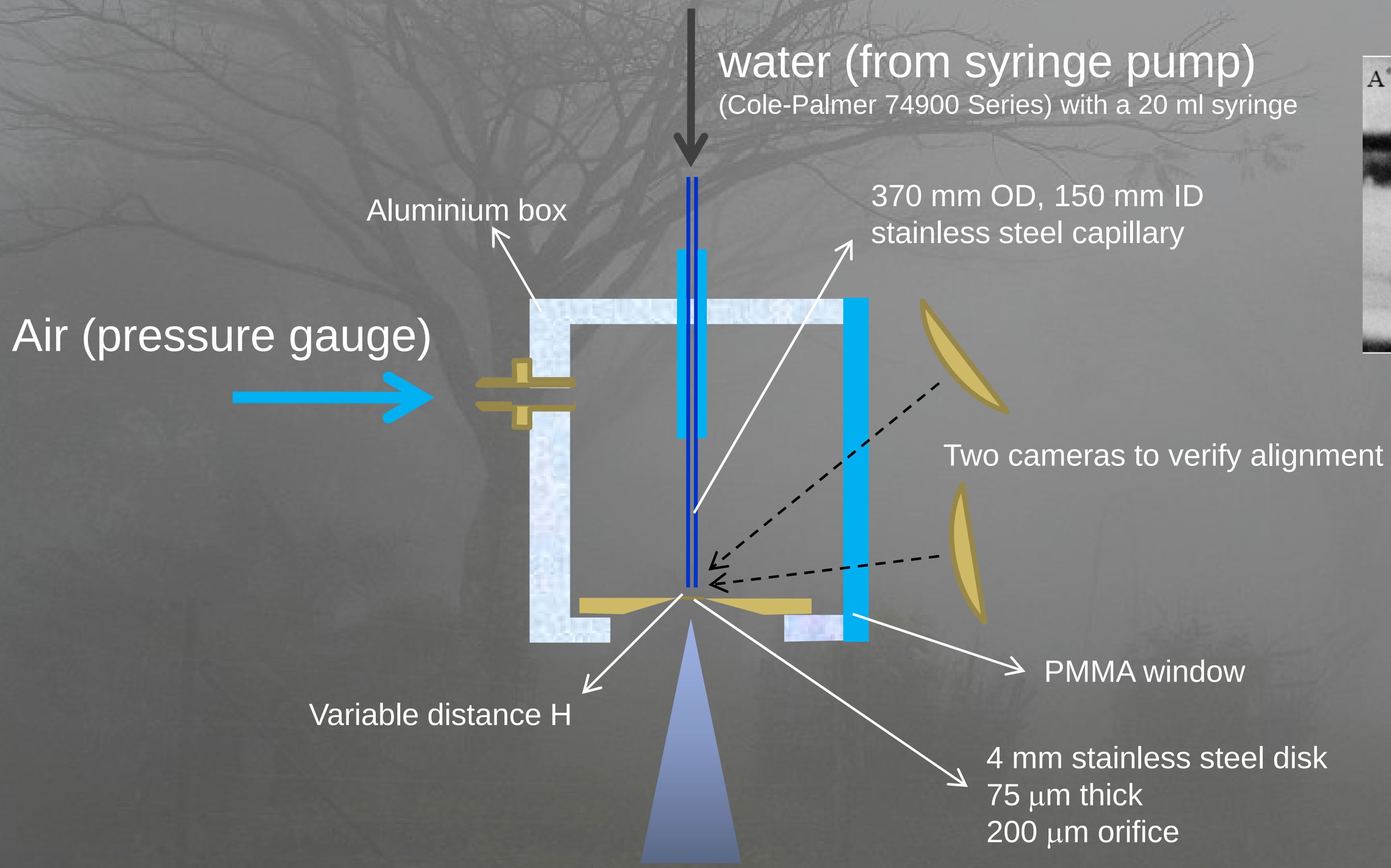
Case 2

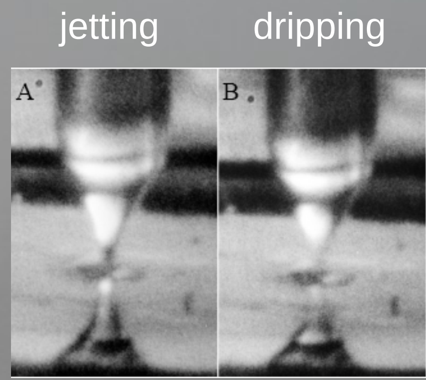
Q=0.00004



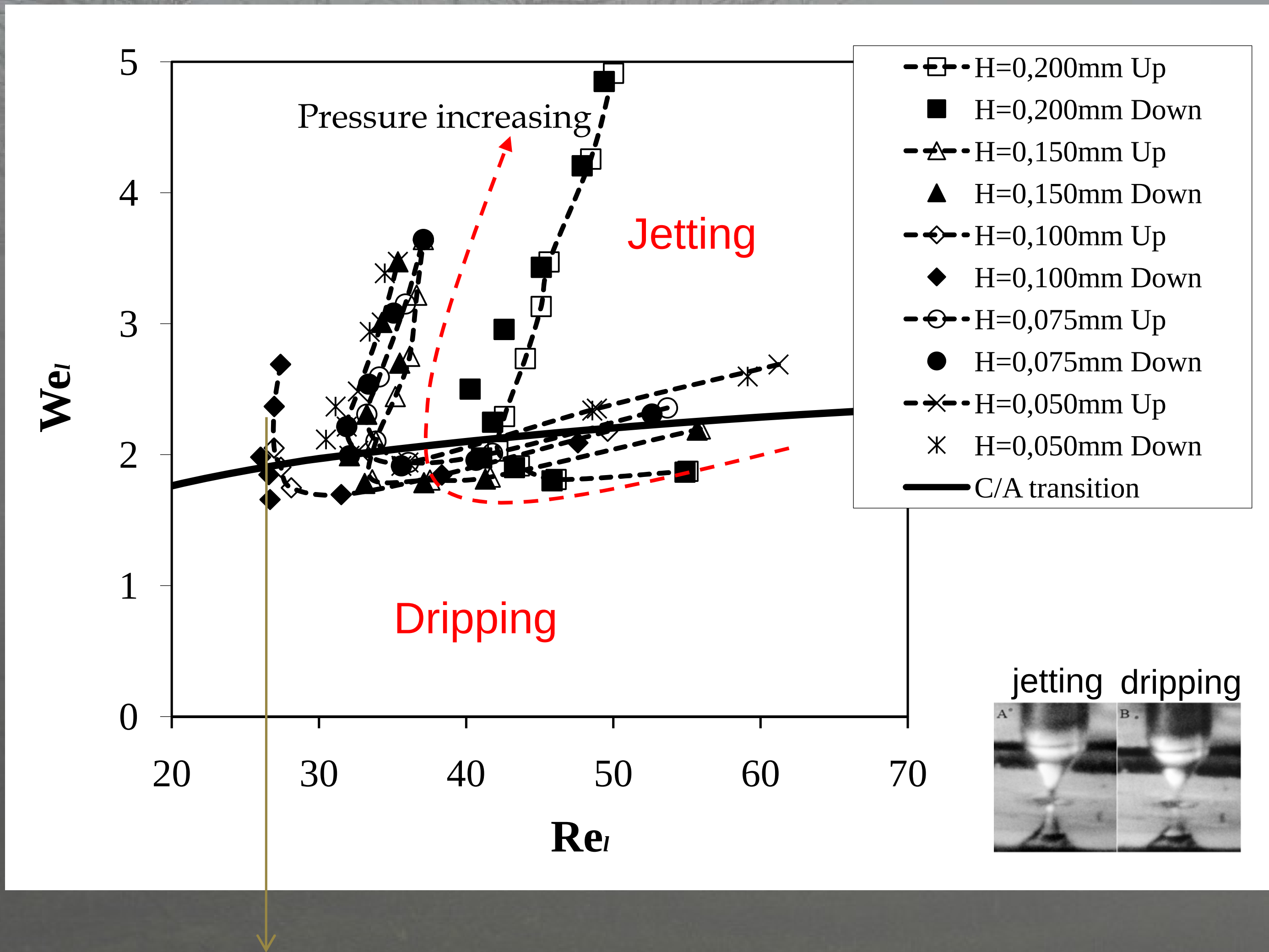
High periodicity near the exit orifice (but not necessarily outside)

Experimental setup



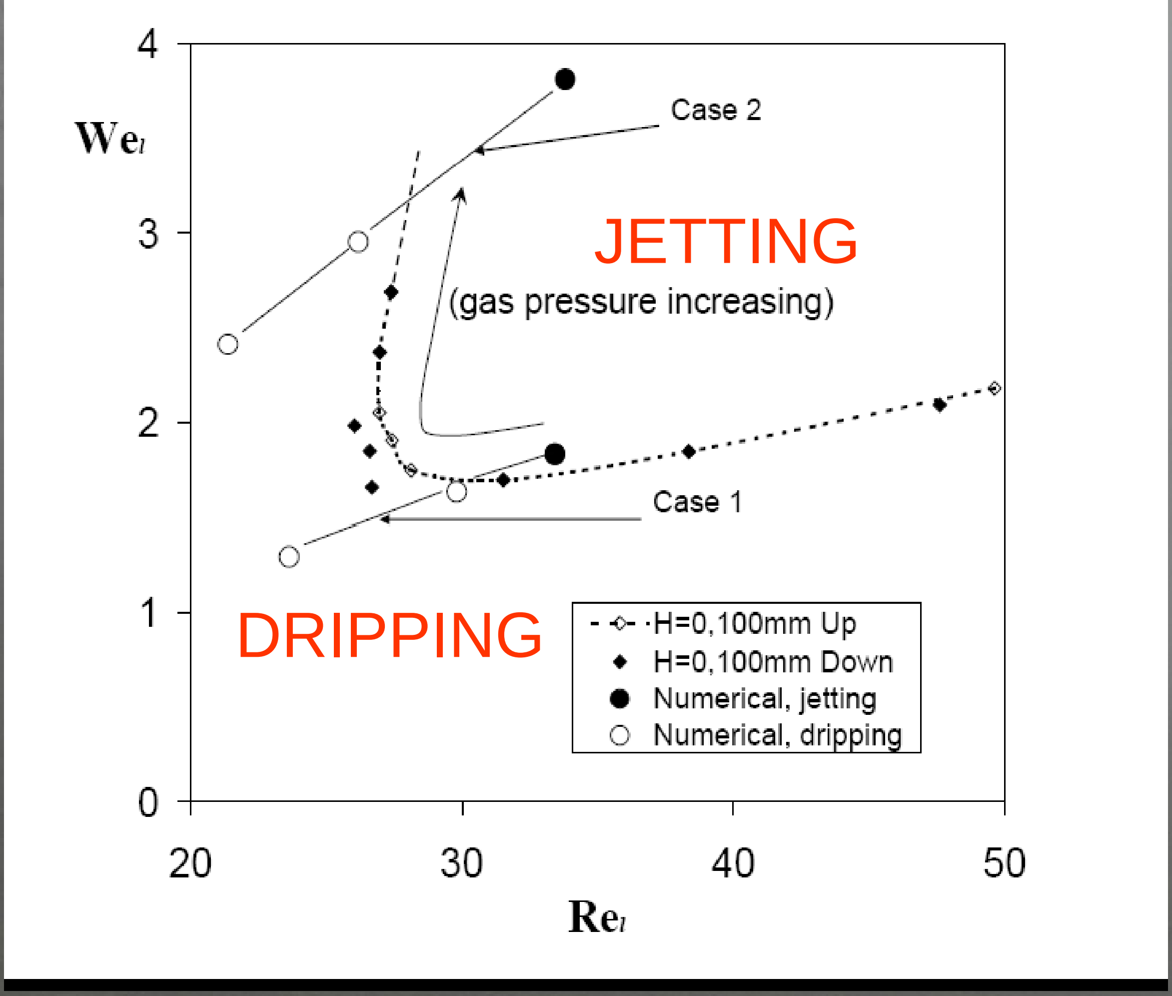


Comparison with experimental results



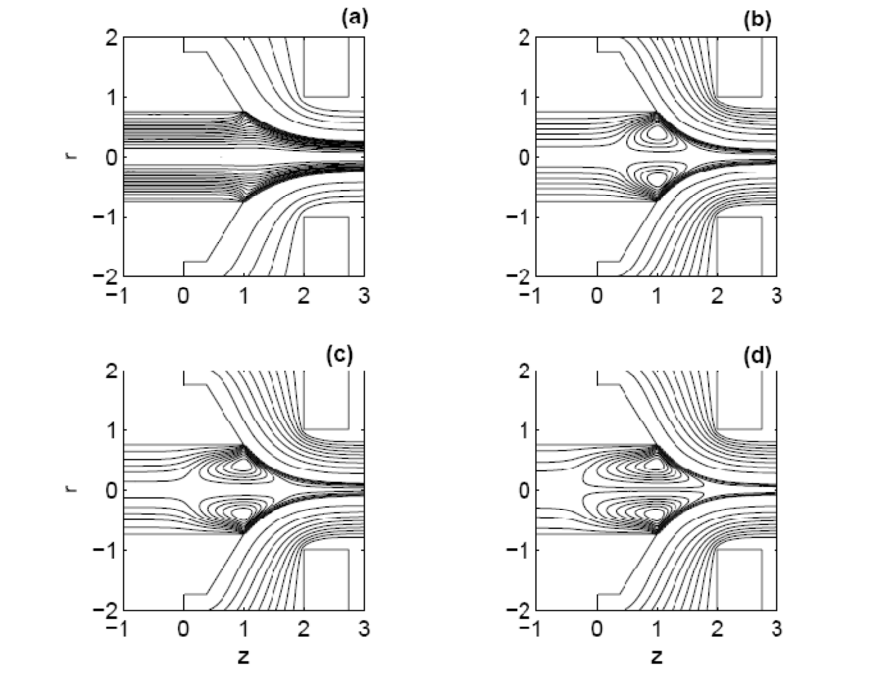
Optimum distance H: H/D~0.5

Experimental and numerical dripping to jetting transition

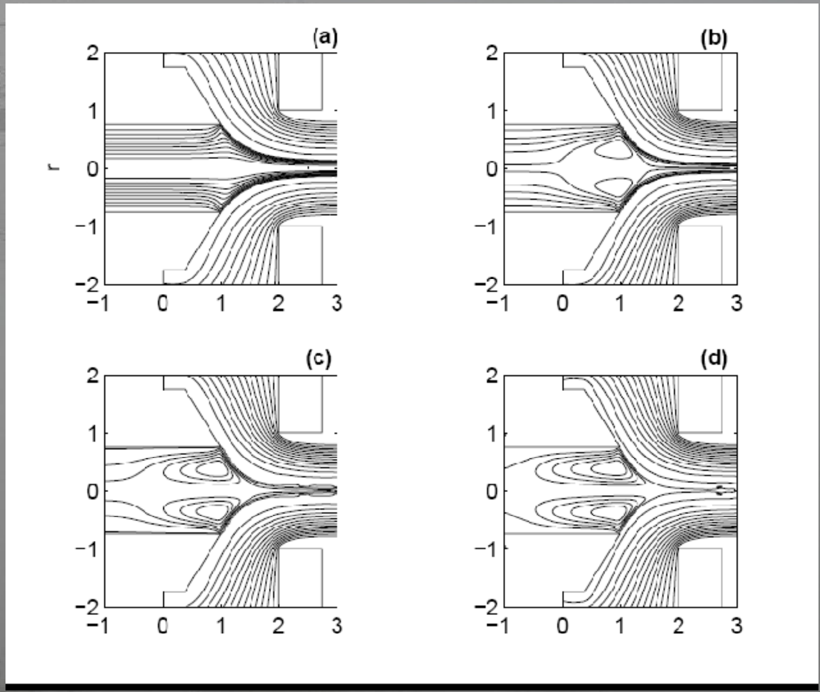


Flow structure inside the meniscus

Case 1



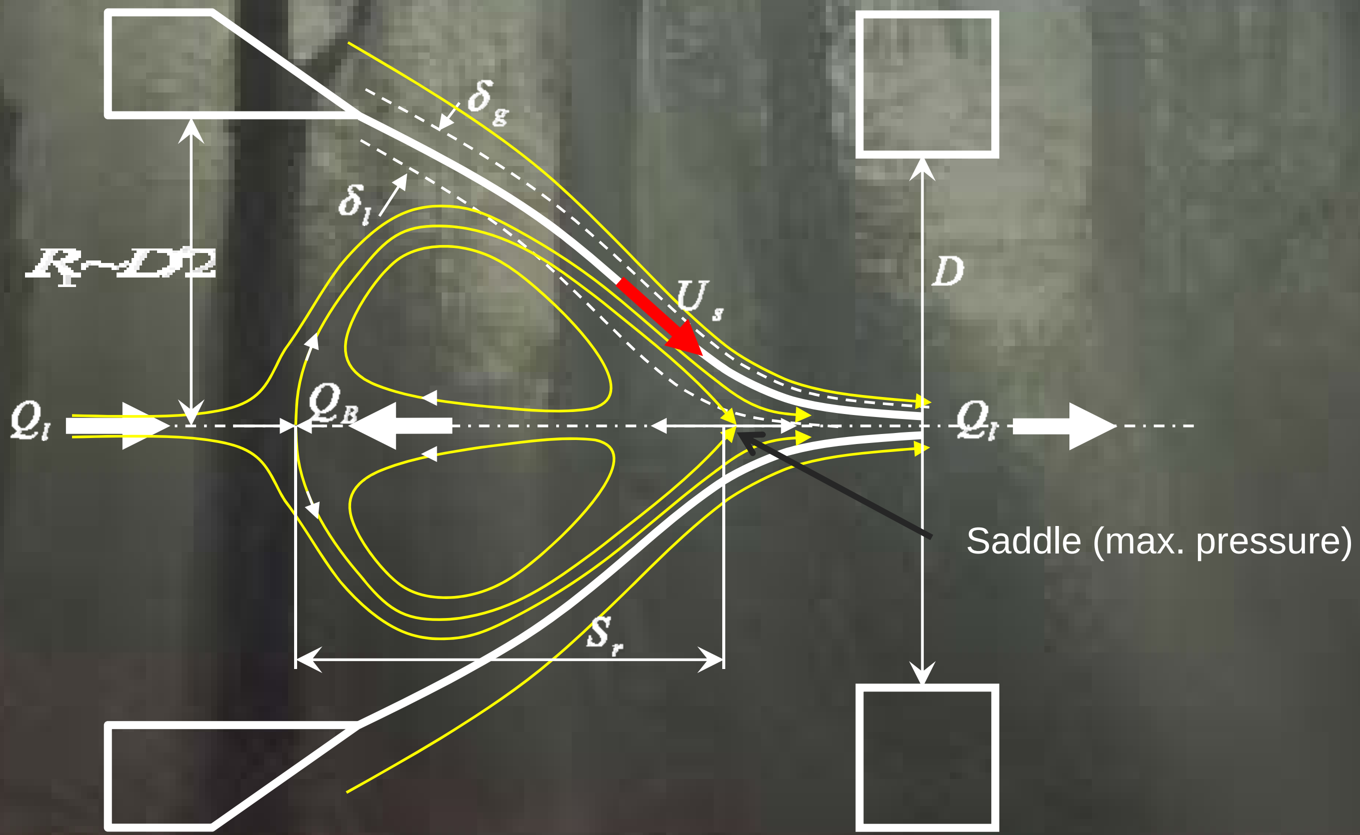
Case 2



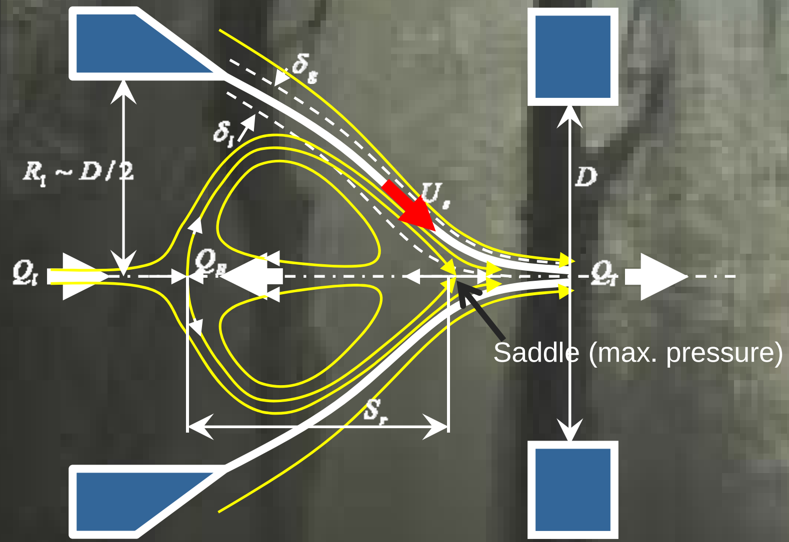
Experimental observations of recirculation cells:

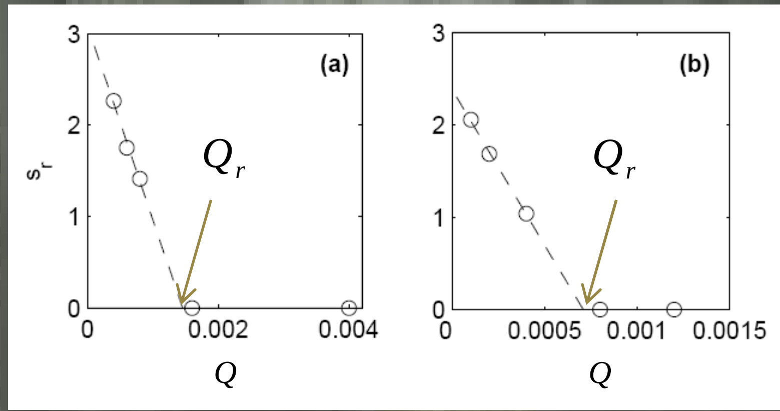
- Co-flowing systems:
  - S. L. Anna and H. C. Mayer, Phys. Fluids, 18, 121512 (2006).
  - R. Suryo, O. A. Basaran, Phys. Fluids, 18, 082102 (2006)
- Taylor cones: Barrero et al. Phys. Rev. E, 58, 7309-7314 (1998)

Flow structure inside the meniscus



Flow structure inside the meniscus





$$\delta_l \sim (\mu_l R / \rho_l U_s)^{1/2}$$

$$Q_R = U_s / \delta_l^2$$

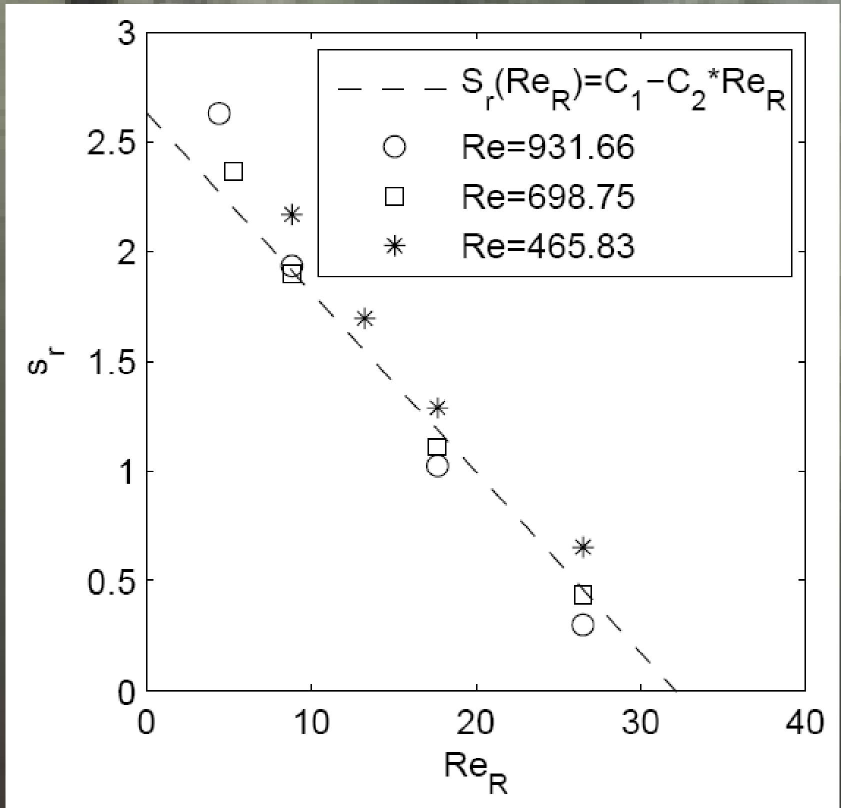
$$Q_r = Q_R / Q_g \sim U_s/(\delta_l^2 Q_g) \sim \mu_l R / (\rho_l Q_g) = \tfrac{\rho}{\mu} \mathrm{Re}^{-1}$$

$$Q_B = Q_R - Q_l$$

$$\frac{\mu_l S_r}{\rho_l Q_B} \sim O(1)$$

$$S_r \sim \rho_l (Q_R - Q_l) / \mu_l \Rightarrow s_r = S_r / R = C_1 - C_2 \mathrm{Re}_R$$

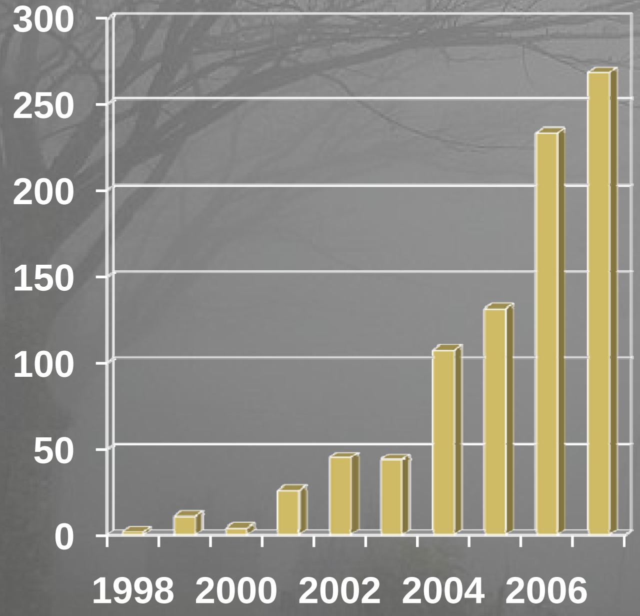
Flow structure inside the meniscus



$$s_r = C_1 - C_2 \,\mathrm{Re}_R$$

History. Flow Focusing

Articles per year
Subject: Flow Focusing
(Source: Scopus)

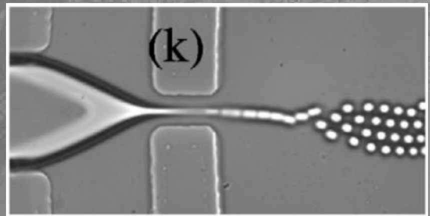


*“**Gañán-Calvo [21] pioneered the use of a technique now called flow-focusing where he used a co-flowing accelerating gas stream to reduce the radius of a liquid jet issuing out of a nozzle.[32]** He showed that a nearly monodisperse spray is produced when the Weber number, which characterizes the relative importance of inertial force in the gas phase to the surface tension force, lies below a critical value.”*

Suryo, R. & Basaran O. A. (2006) *Phys. Fluids* **18**, 082102

History. Flow Focusing

Most work (experimental) has been devoted to liquid-liquid FF in microfluidics



("planar" FF)

• Anna, S.L., Bontoux, N., Stone, H.A. (2003), *Appl. Phys. Lett*. **85**, 364 **(cited by 199)**

…or gas in liquid FF (microbubbles) in microfluidics

• Ganan-Calvo, A.M., Gordillo, J.M., (2001), *Phys. Rev. Lett*. **87**, 274501 **(cited by 89)**

• Garstecki, P., Gitlin, I., Diluzio, W., Whitesides, G.M., Kumacheva, E., Stone, H.A. (2004), *Appl. Phys. Lett*. **85**, 2649 **(cited by 66)**

History. Flow Focusing

… however, the original liquid-in-gas configuration has been subject of smaller attention:

- Ganan-Calvo, A.M. (1998), *Phys. Rev. Lett*. **80**, 285 **(cited by 69)**
- Almagro, B., Gañán-Calvo, A.M., Canals, A. (2004), *J. Anal. Atom. Spectrom.*, **19**, 1346 **(cited by 5)**
- Arumuganathar, S., Irvine, S., McEwan, J.R., Jayasinghe, S.N. (2008), *J. Appl. Polymer Sci*. **107**, 1215


10 years of Flow Focusing (1998-2008)
THANK YOU
IPPT PAN Seminars. Warsaw, January 2008