The mysteries of droplet birth in microfluidic cross junctions

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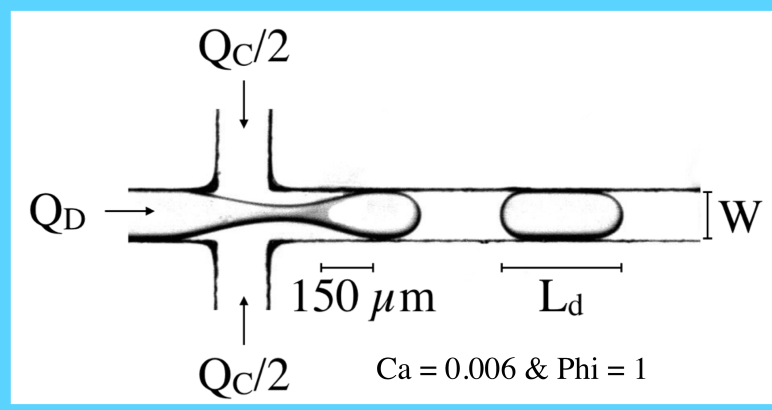
« How to predict droplet volume and frequency based on inlet flow rates? »

Introduction

- Experiments on droplet formation in symmetric cross junction → the simplest geometry.
- With and without surfactant.

- Different production regimes are observed as Capillary number (Ca) and flow rate ratio (ϕ) are varied in a large range.



Parameters

Fixed: H, W, μ_D, μ, σ Varied: Q_D, Q_C

$$W^* = \frac{W}{H} \qquad Ca = \frac{1}{WH}\frac{\mu Q_C}{\sigma}$$

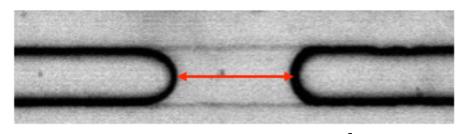
$$\eta = \frac{\mu_D}{\mu} \qquad \phi = \frac{Q_D}{Q_C}$$

Dimensionless

Output: L_d, F_d

$$\Omega_d = \frac{Q_D}{F_d}\frac{1}{W^2 H}$$

Satellite droplets

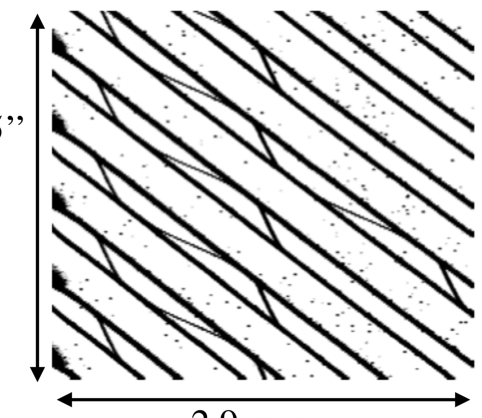


Ca = 0.007 & Φ= 1.5

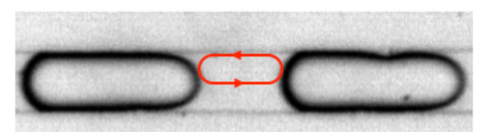
Satellite droplet looping in the vertical plane between two main droplets.

Recirculation → Stokes eq. solved analytically :

$$\frac{U_{sat,Max}}{U_d} = f(W^*) = 1.78 \Rightarrow W^* = 1.8$$



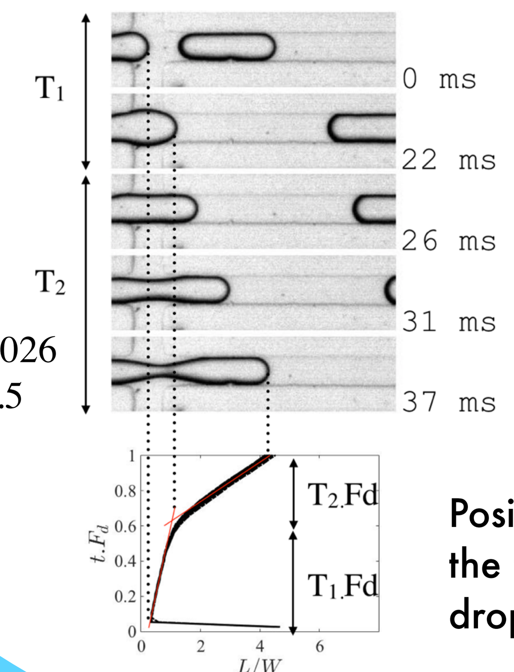
Spatio-temporal diagram



Ca = 0.012 & Φ = 1.5

Satellite droplet looping in the horizontal plane between two main droplets.

Time decomposition



Ca = 0.0026 & Φ = 0.5

Dripping in two steps: inflation (T_1) and squeezing (T_2).

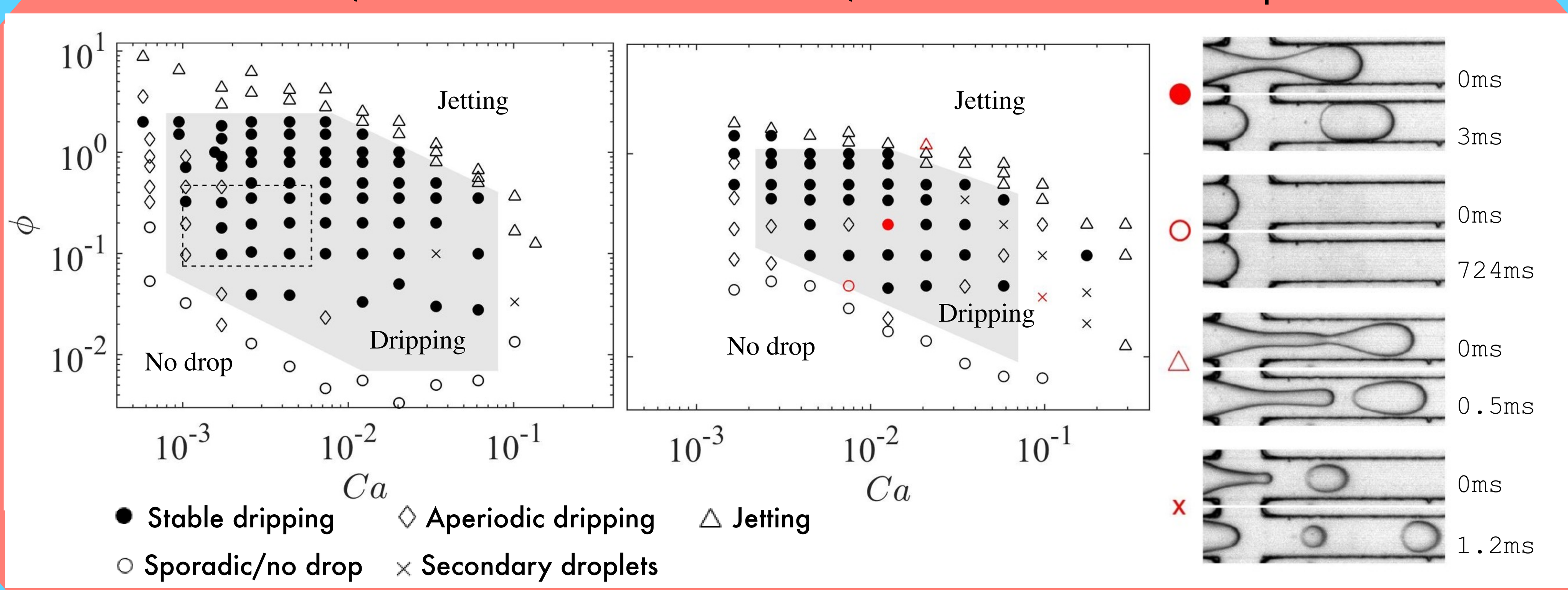
$$\Omega = \frac{Q_D}{F_d}\frac{1}{W^2 H} = (T_1 + T_2) Q_D \frac{1}{W^2 H}$$

$$= \Omega_1 + \Omega_2 \phi$$

Position of the front interface during the formation of 10 successive droplets.

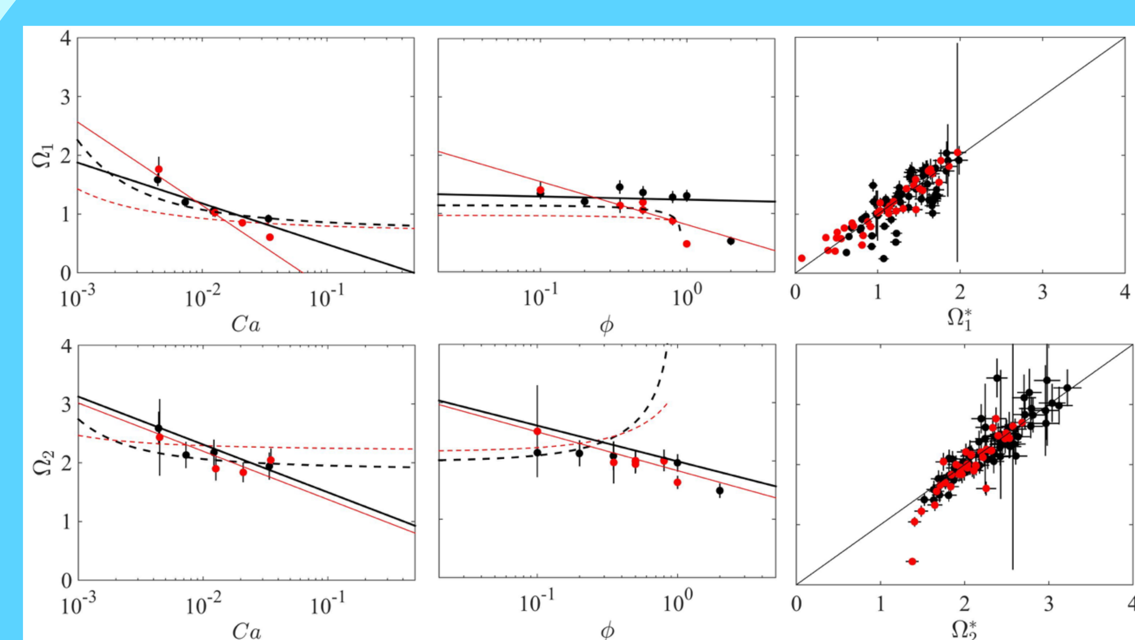
Phase diagrams

without surf., W* = 1.8 with surf., W* = 3.2 Snapshots



- Stable dripping over several decades of Ca and ϕ
- Range reduced with surfactant.

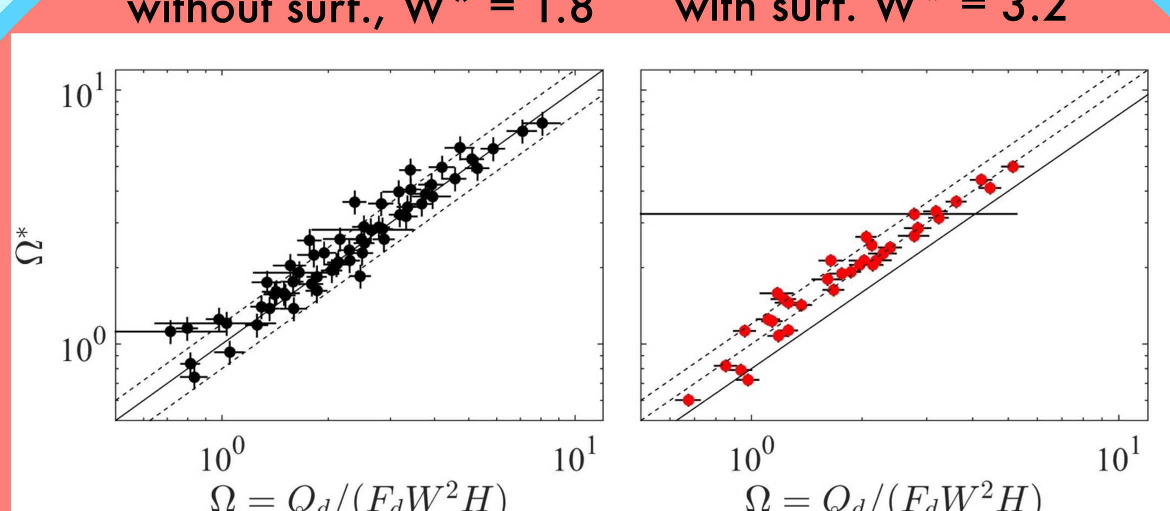
Ω₁, Ω₂



Ω_1 & Ω_2 vs. Ca (resp. ϕ) with fixed ϕ (resp. Ca).
Solid line = fit on the whole dataset. Dashed line = model of Chen et al. [1].
● without surf. ● with surf.

Prediction of Ω

without surf., W* = 1.8 with surf. W* = 3.2

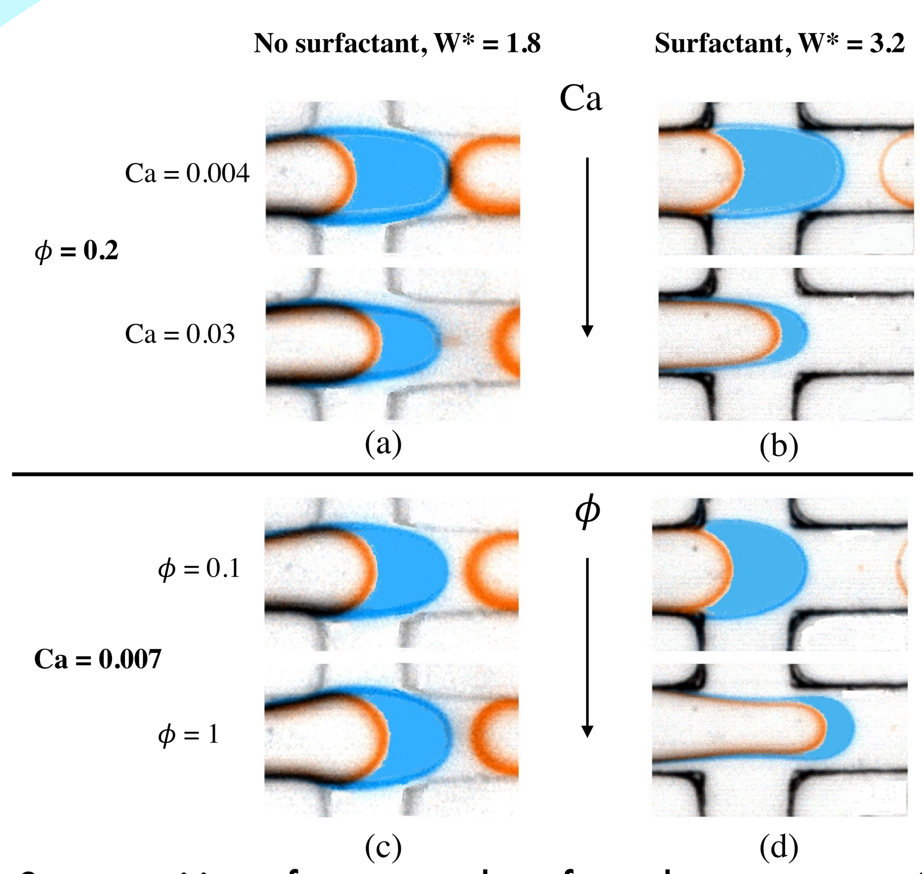


Parity plot of measured dimensionless droplet volume Ω vs. empirical law :

$$\Omega_i^* = A_1 - B_i \log Ca - C_i \log \phi$$

Step *i*	1: Filling		2: Pinching	
Surfactant	w/o	w/	w/o	w/
A_i	−0.25 ± 0.04	−2.21 ± 0.03	0.25 ± 0.04	0.09 ± 0.03
B_i	0.7 ± 0.01	1.42 ± 0.01	0.81 ± 0.01	0.82 ± 0.01
C_i	0.05 ± 0.03	0.74 ± 0.03	0.61 ± 0.03	0.67 ± 0.03

Inflation : dispersed volume



Superposition of two snapshots from the same experiment right after pinch-off and initial retraction (orange) and after T1 at the end of the inflation step (blue).

- Ω_1 ↘ with Ca ↗ (more pronounced with surfactant)
- Ω_1 ↘ with ϕ ↗ (only with surfactant)

Conclusion

- Model valid for large range of Ca & ϕ (extended range compared to previous models - limits of Chen's model)
- Influence of surfactant mainly on T_1
- Aspect ratio W* determined from satellite droplets.

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Acknowledgments
This research has been funded by the FNRS (FRIA) and the Interuniversity Attraction Poles Programme (IAP 7/38 MicroMAST), initiated by the Belgian Science Policy Office.

References
[1] Chen et al., Microfluid. Nanofluid., 2014, 18.