Novel Insights into Droplet Generation Mechanisms at Microfluidic Cross-Junctions

INSTITUTE OF FUNDAMENTAL TECHNOLOGICAL RESEARCH
POLISH ACADEMY OF SCIENCES

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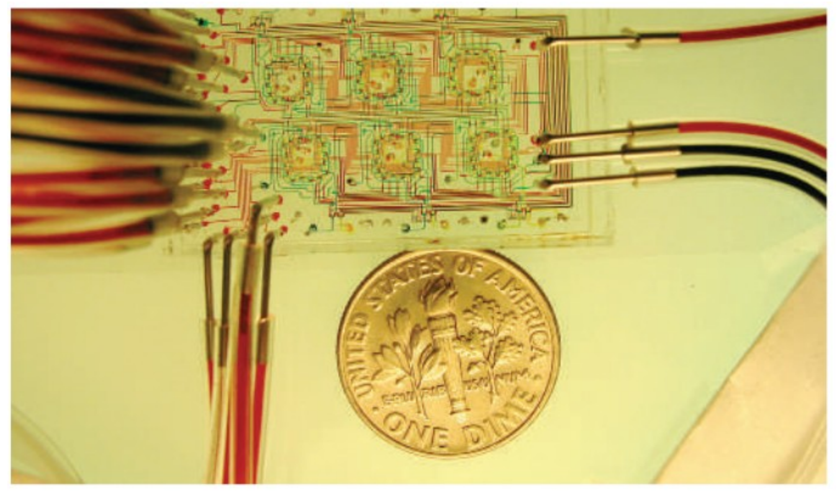
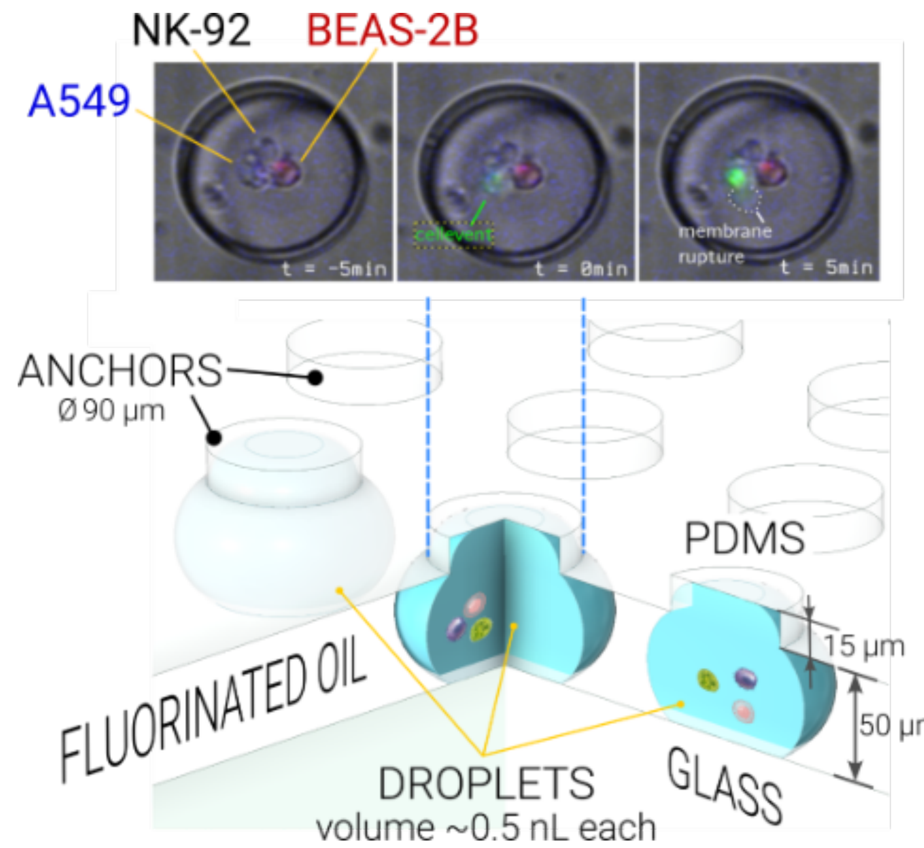
Introduction: Droplet Microfluidics

- Multiphase flow in microchannels with characteristic dimensions ranging from tens to hundreds of microns.



- interface forces >> body forces

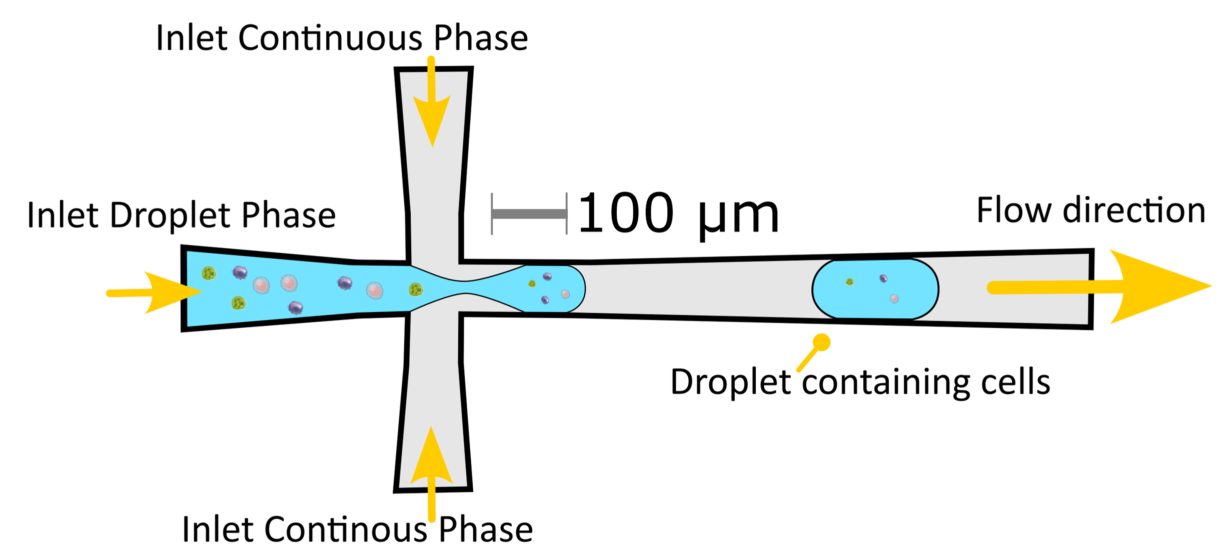
- Droplet-based microfluidics provides: micro-scale compartmentalization, process automation, minimal reagent consumption, and high-throughput analysis.



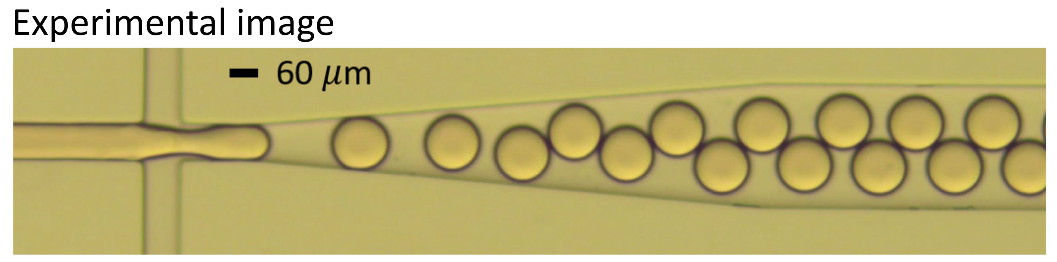
Kurniawan T. (2025)

Critical part: The droplet generator

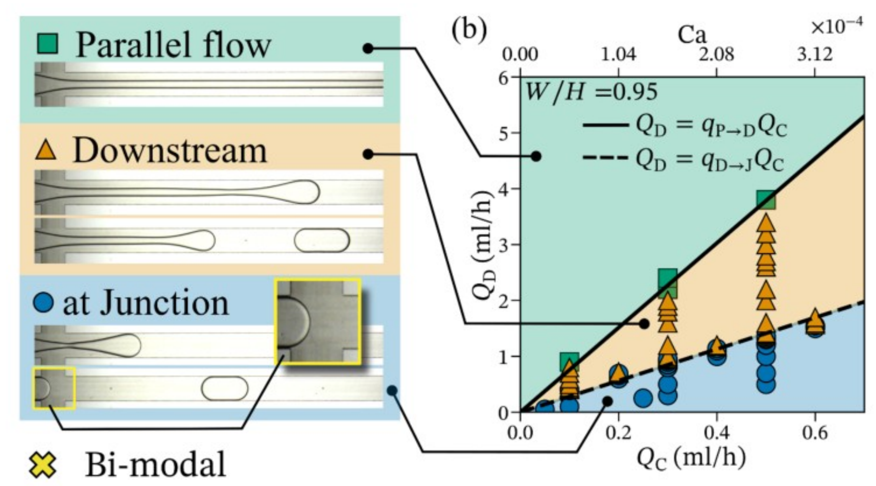
- Droplet formation in a microfluidic cross-junctions



Experimental image



- Flow Pattern emerges from the two-phase flow depends on various factor:
  - flow conditions: flow rates ratio
  - fluid properties: viscosties, interfacial tension
  - channel geometry
  - liquid-surface condition: wetting condition
- Important dimensionless numbers: Reynolds (Re) and capillary (Ca) numbers.



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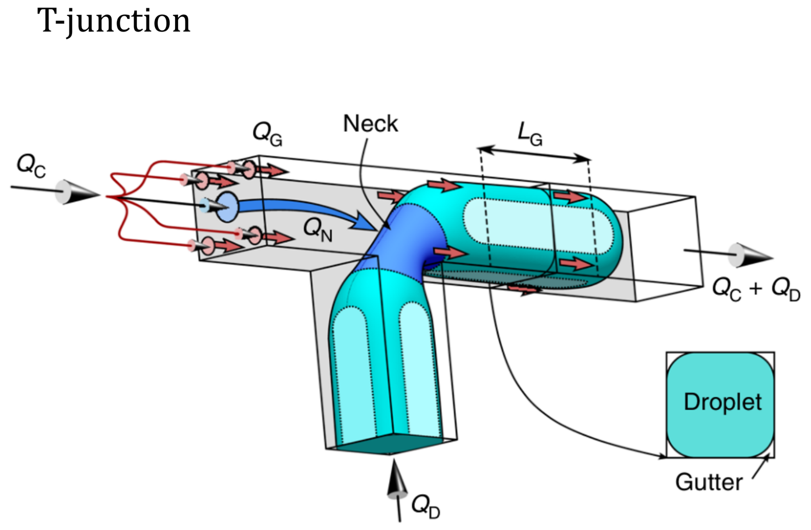
Interesting multiphase flow problem : recent experimental insights

- Leaking flow through the gutter causing Ca-dependency of the droplet formation.
- Leaking flow behaves differently with different junction geometry

T-junction

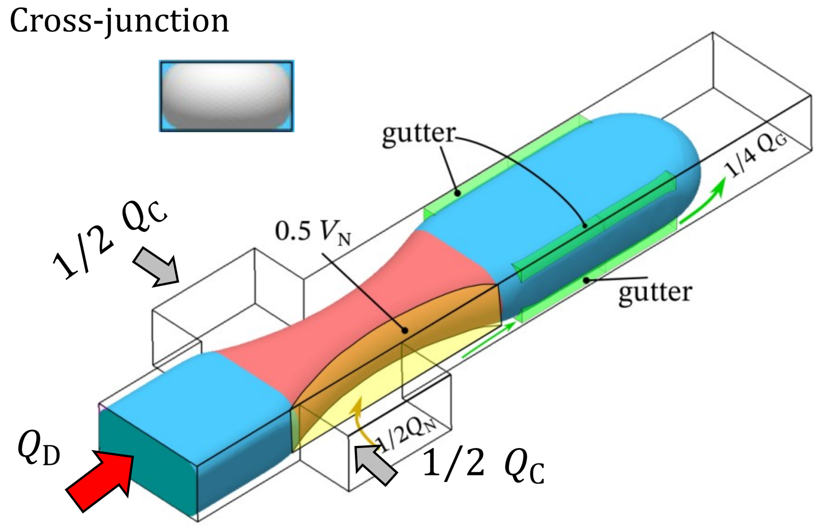


$$q_N = \frac{q\mathrm{Ca}}{q\mathrm{Ca}+\beta}$$

q_N : ratio of the necking flow rate to the CP flow

(Korczyk et. al. 2019)

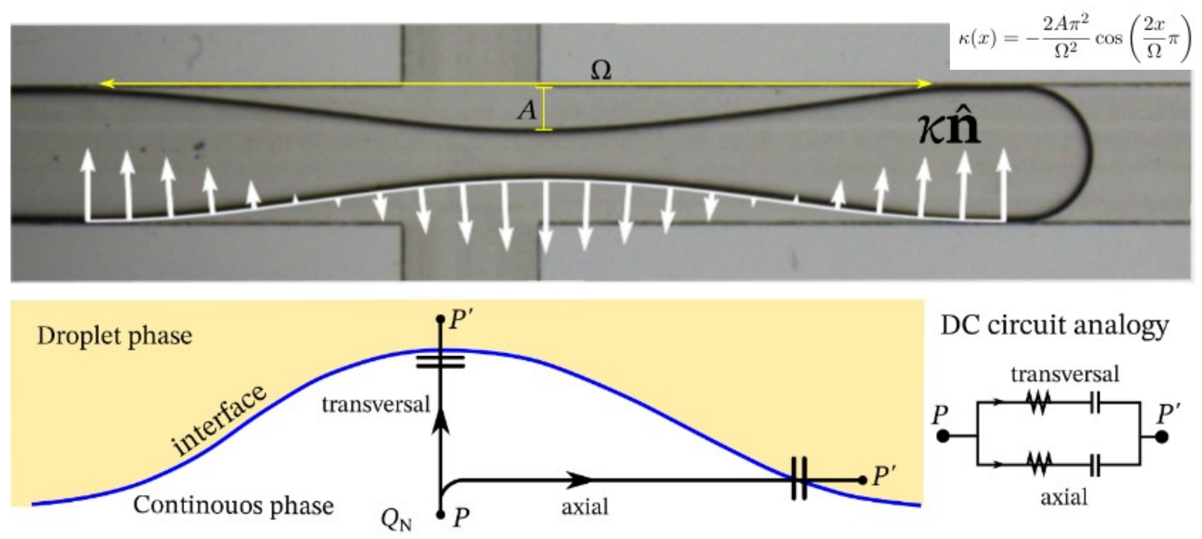
Cross-junction



$$q_N = 1 - \frac{\kappa}{\mathrm{Ca}\,(l_0 + qt^*)}$$

(Kurniawan et. al. 2023)

- In cross-junction device, the droplet interfacial forces allows the elongation of the neck shape and therefore causing the increase of necking process duraiton.

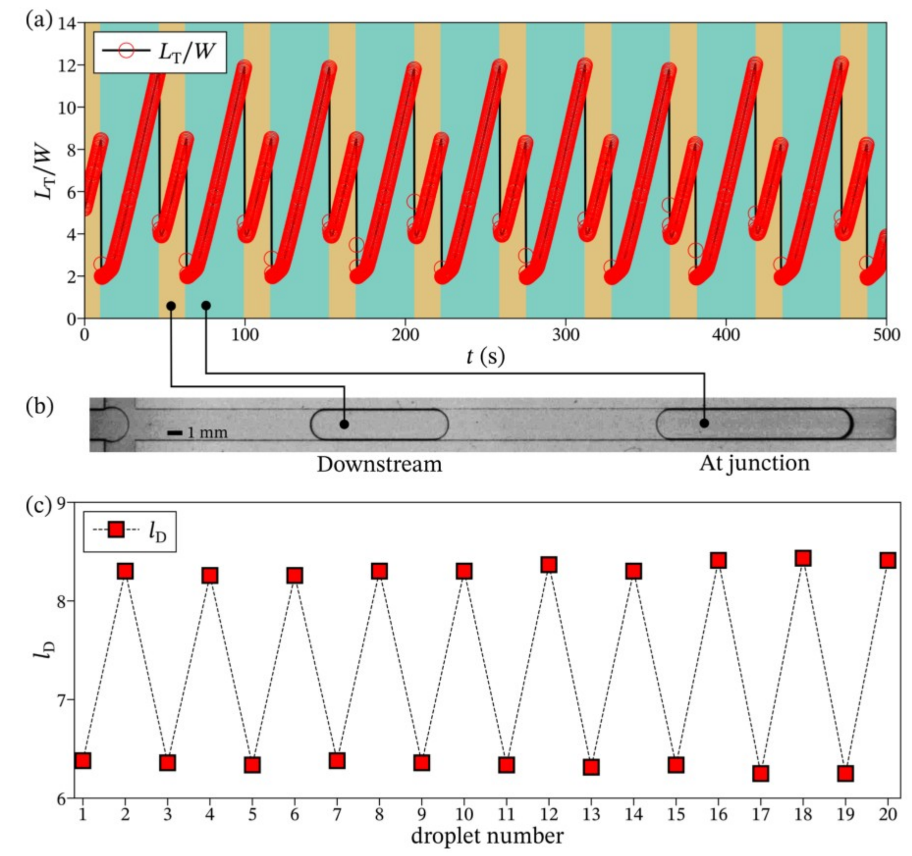


$$\frac{\mu_C}{\Xi}\frac{d\Omega}{dt} = \frac{\mu_C}{\Lambda}\frac{dA}{dt} + \gamma\frac{A}{\Omega^2}$$

differential equation describing the neck shape evolution

(Kurniawan et. al. 2023)

- Varying the channel geometry in a cross-junction microfluidic device enables the generation of multiple droplet sizes while maintaining constant input flow rates.



Work in progress. Preliminary result in Kurniawan T. (2025)

References:
1. Balagaddé, F. K. et al. Science 309, 137–140 (2005).
2. Korczyk, P. M. et al. Nat. Commun. 10, 2528 (2019).
3. Kurniawan, T. et al. Chem. Eng. J. 474, 145601 (2023).
4. Kurniawan, T. Dissertation (IPPT PAN, Warsaw, 2025).

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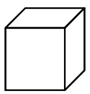
Lagrangian Approaches to Multiphysics Two-Phase Flows
8 – 12 September 2025
Udine, Italy

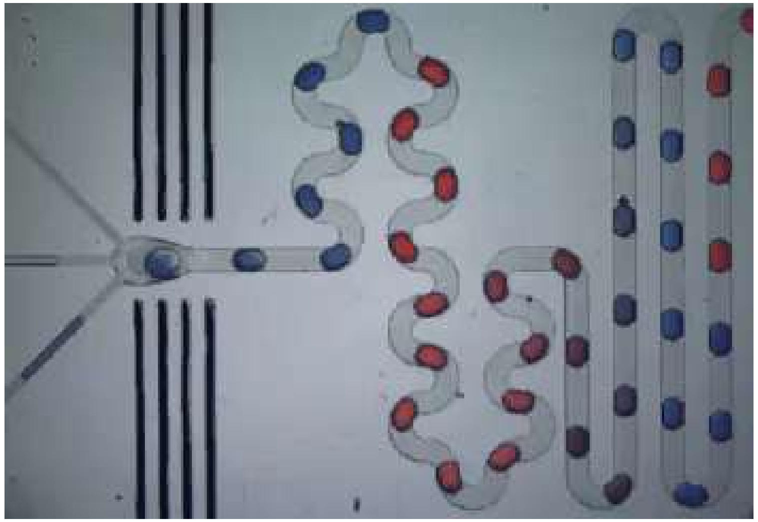
Droplet microfluidics

Force Type	Scaling	Relevance in Microfluidics
Inertial	$\rho\, U^2\, L^2$	Negligible (low Re)
Viscous	$\mu U L$	Dominant
Surface	$\gamma\, L$	Comparable/dominant
Body	$\rho g L^3$	Usually negligible

L 

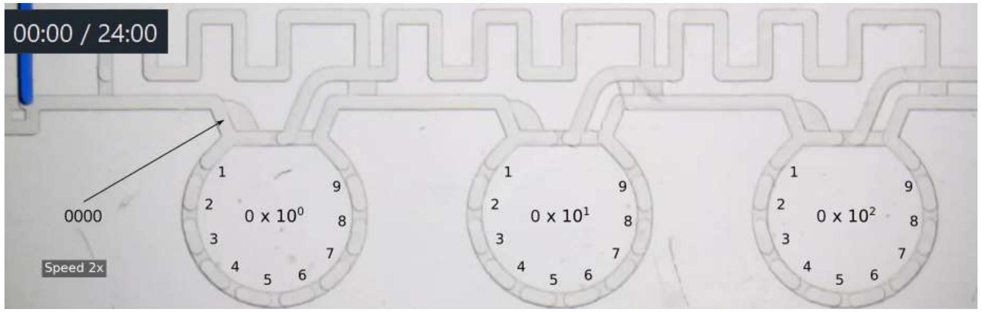
L: length scale

ρ: density,
U: characteristic velocity
γ: surface tension
g: gravity



High through-put reaction scanning

Churski (2010)



Microfluidic counter

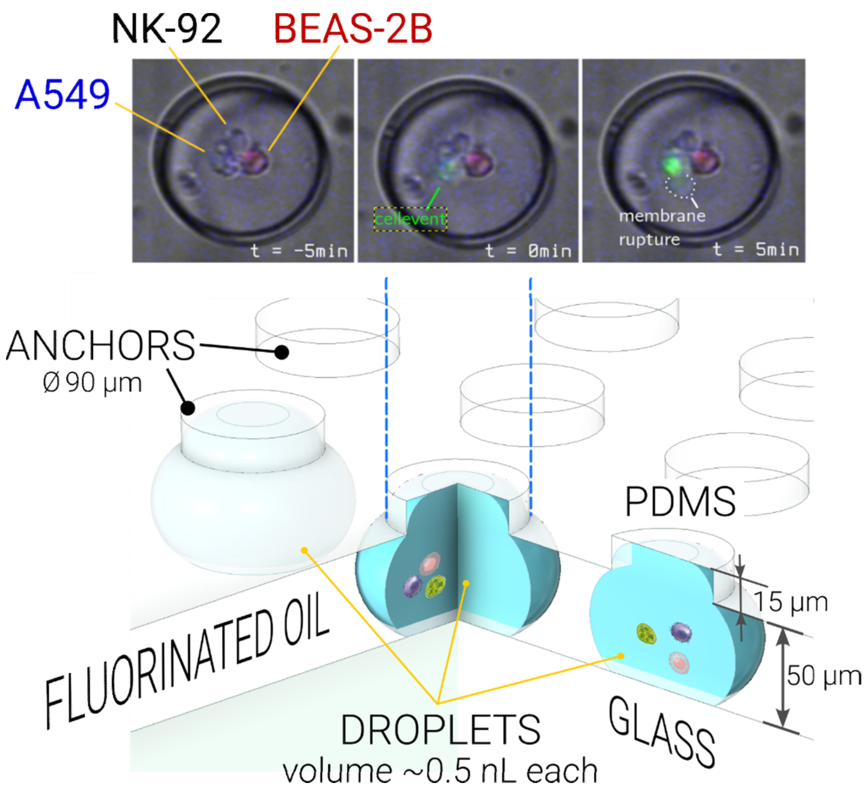
Zaremba (2021)

Why use droplets?

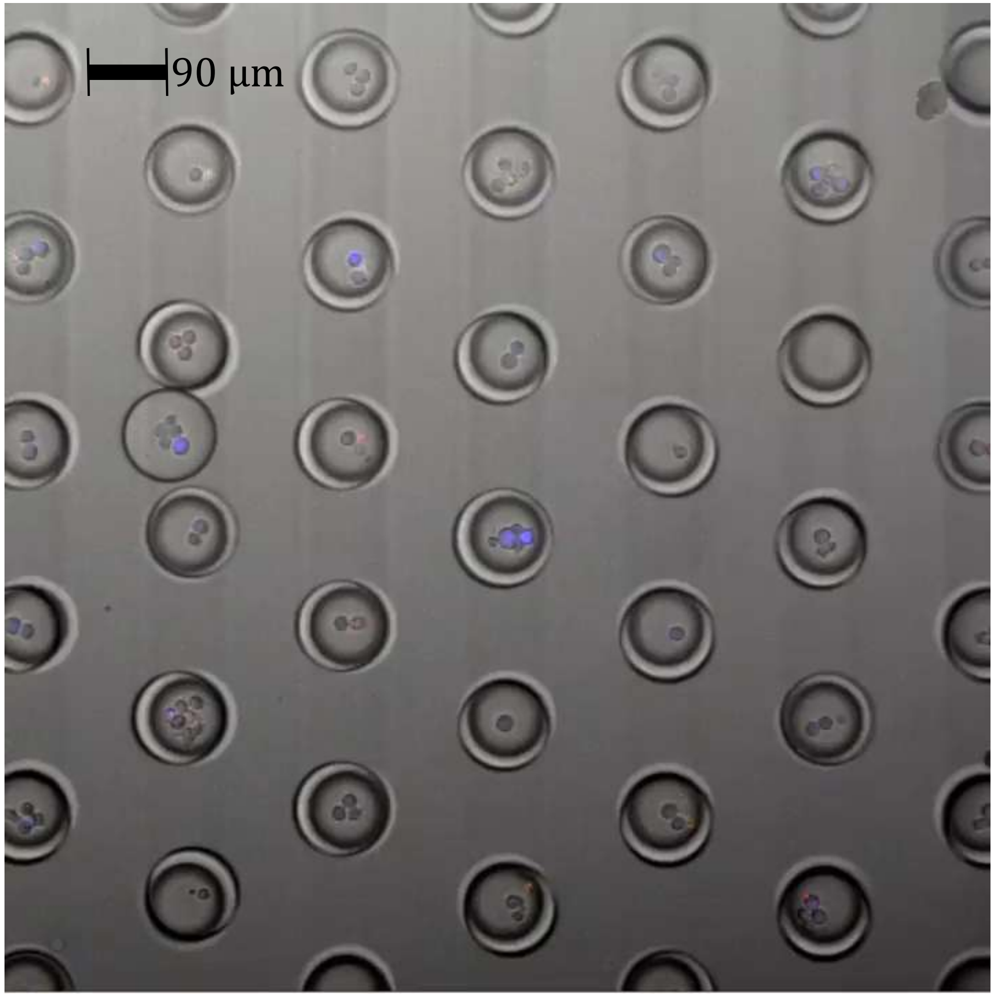
- ❑ Compartments that allows isolation
- ❑ Offers operation automation
- ❑ Low reagents consumption
- ❑ Offers operations of large numbers of micro-sized reactors,
- ❑ high throughput experiments

Example application

3D illustration and real experimental images



24 h observation of Cancer cells (A549/Blue) + Natural Killar cells (not stained) inside droplets.



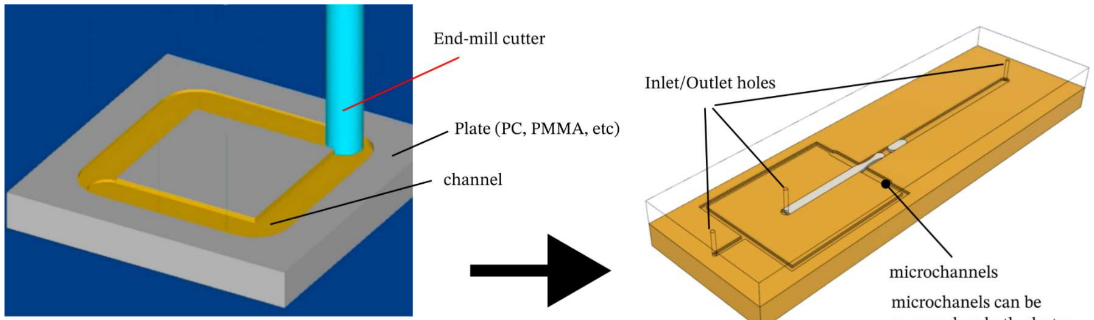
Frame rate is 1 frame per 15 minute
There are 96 cycles = 24 hr observation
Shown here is one position out of 104

Kurniawan T. (2025)

Our microfabrication facility

Fabrication Methods	Resolution		Dimension range of microchannel or structure and its accuracy		Material	Z-step structures
	$X-Y$	Z	**Width** W	**Height** H		
CNC milling	5 μm	5 μm	$W \geq 200\,\mu m$	$H > 5\mu m$, H is limited by flute length	PC, PMMA, etc.	Easy
Photolithog-raphy	1 μm	1 μm †	$W > 1\mu m$	$H \leq 2W$ †‡	PDMS bonded to a glass	Complicated
Femtosecond Laser-pulse	10 um		20 um		Glass, Polymer	

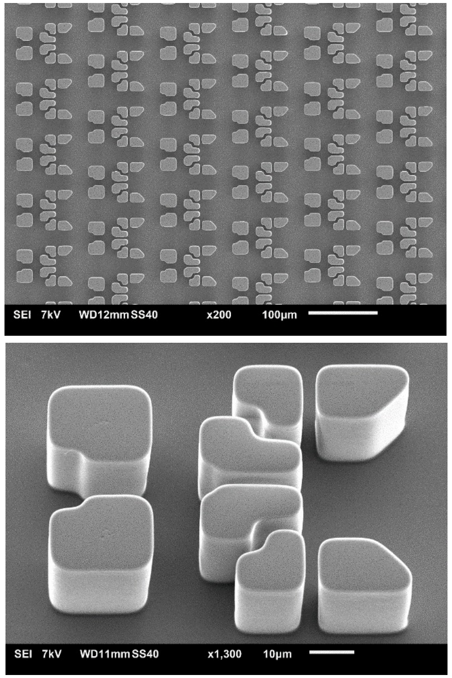
PC: Polycarbonate,
PDMS: Polydimethylsiloxane



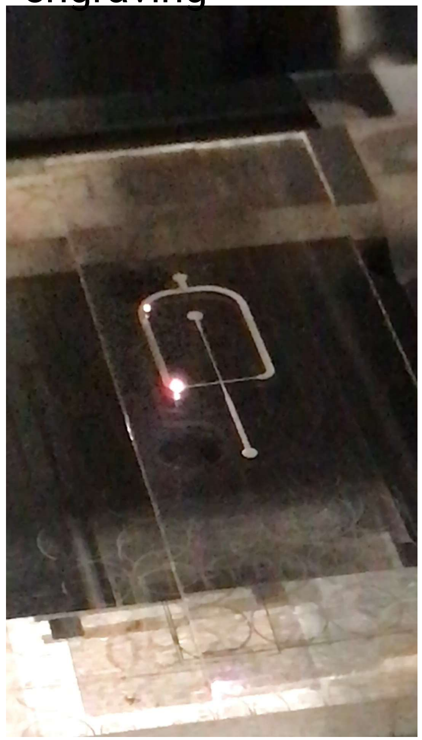
CNC milling process

Cleaning and washing
Bonding: Hot-press method

Photo-lithography

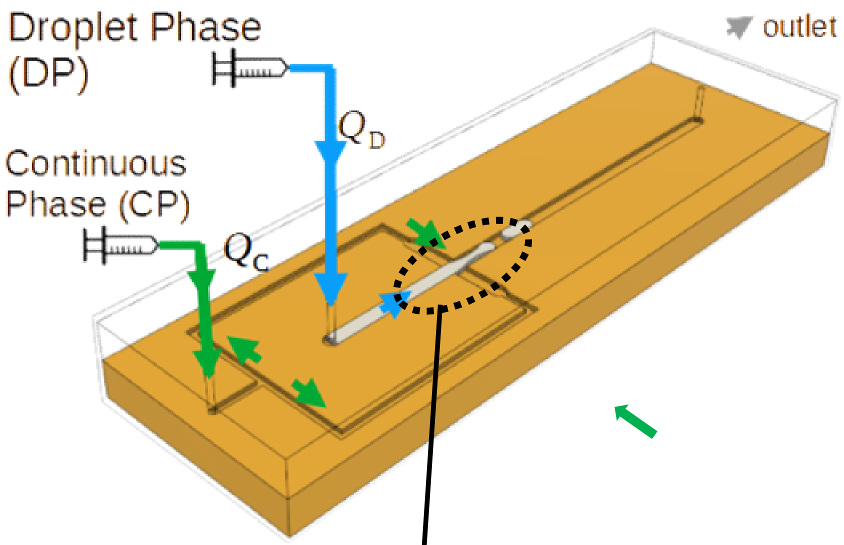


Femtosecond Laser-pulse engraving

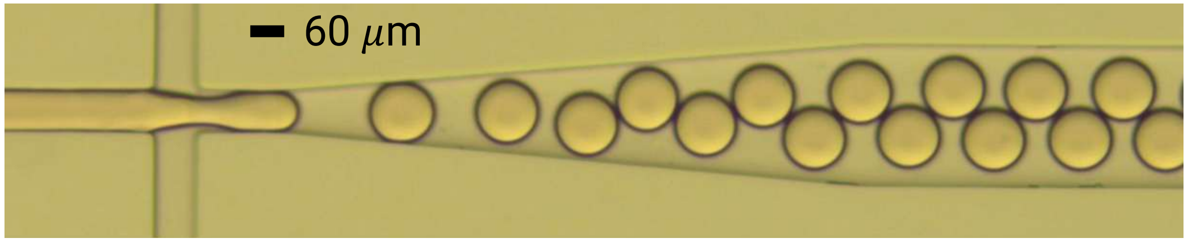


How do we make droplets?

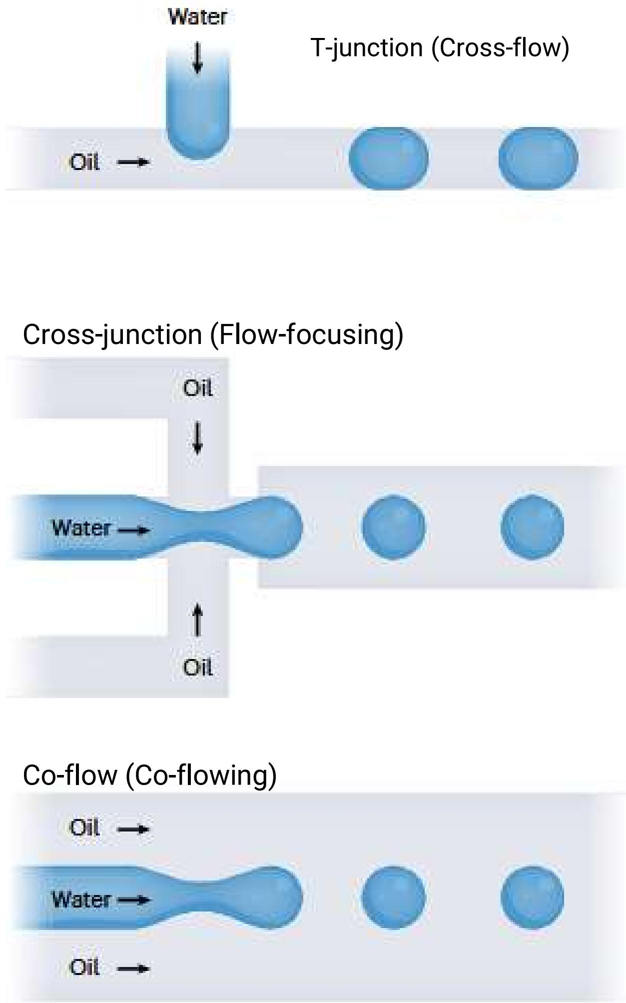
A microfluidic cross junction device



monodisperse droplet generation

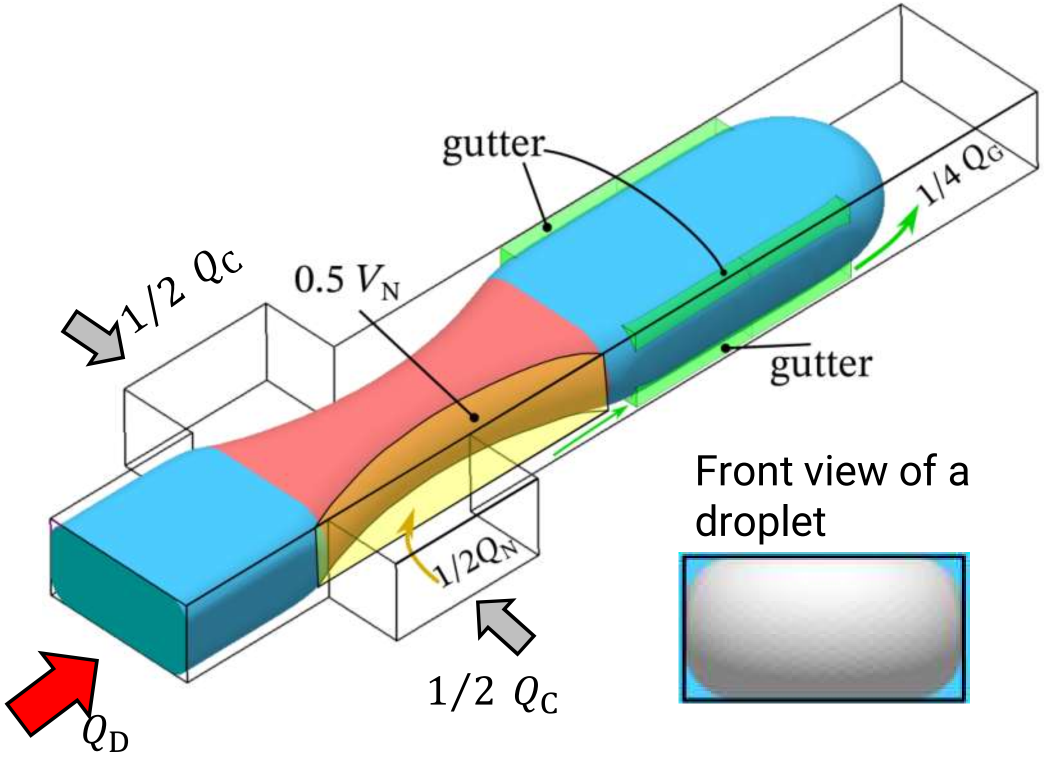


Types of microfluidic junctions

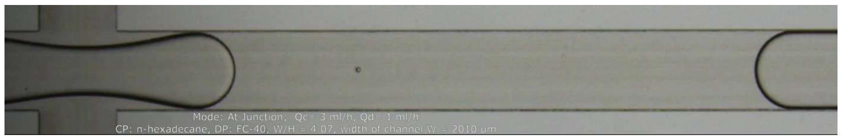


Moragues (2023)

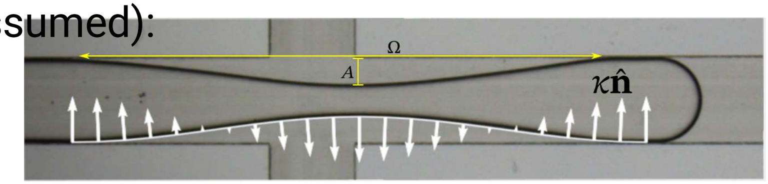
Droplet formation at low capillary number regime

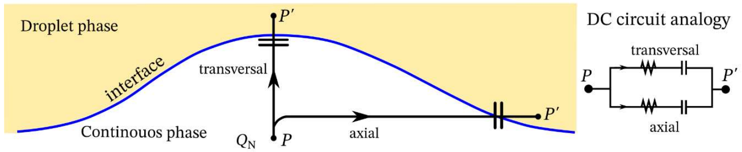


Front view of a droplet



Mathematical modelling (planar droplet was assumed):

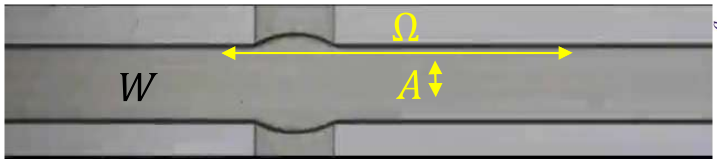


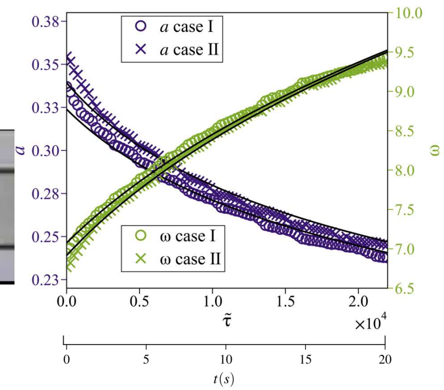


$$\Delta P_{\text{trans}} \approx \Delta P_{\text{axial}}$$

$$\boxed{\frac{\mu_C}{\Xi}\frac{d\Omega}{dt} = \frac{\mu_C}{\Lambda}\frac{dA}{dt} + \gamma\frac{A}{\Omega^2}}$$

Experimental validation

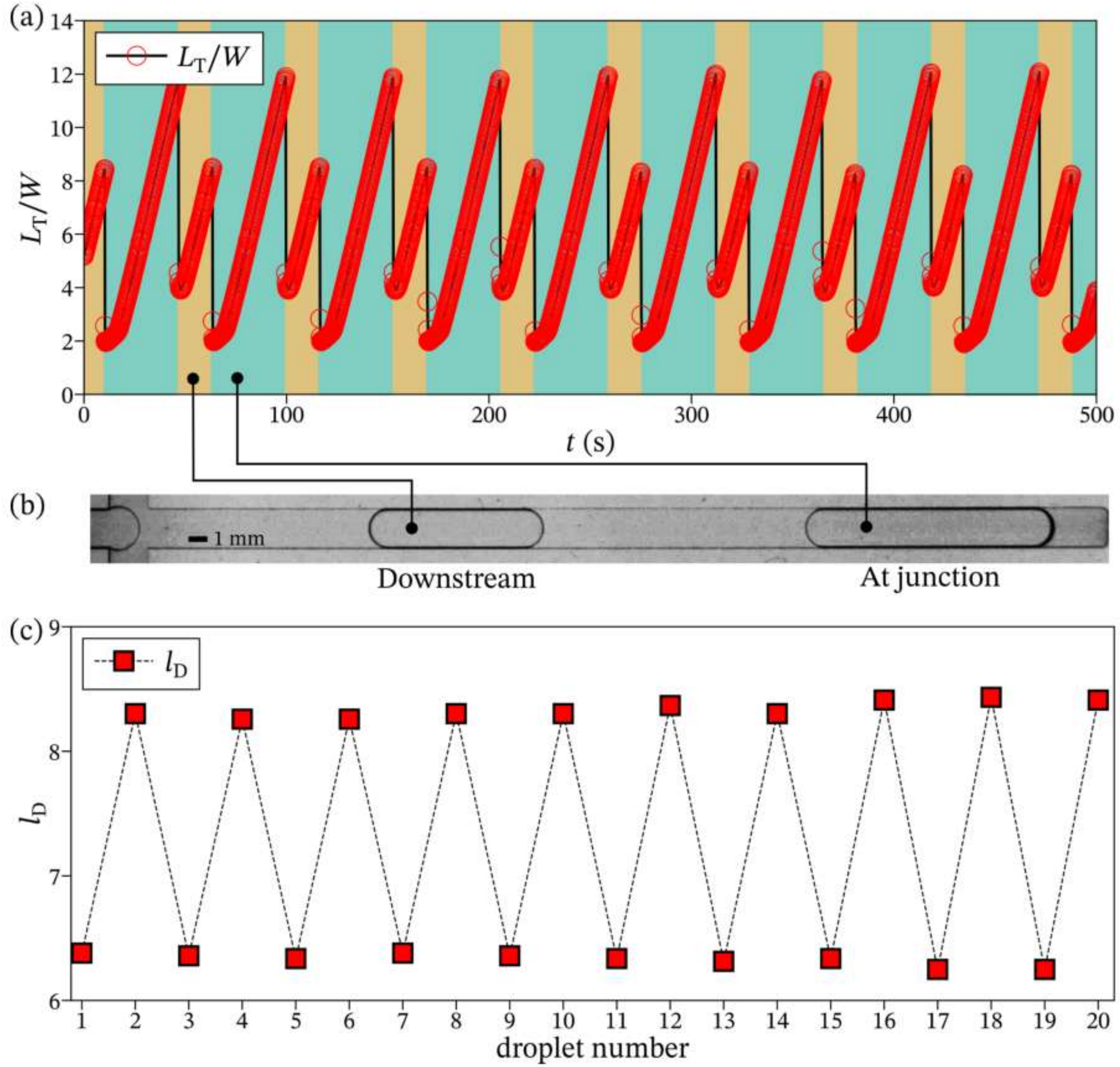




Kurniawan, T. et al. Chem. Eng. J. 474, 145601 (2023).

Current/Future work

- Special flow pattern: Bi-modal
- Oscillation of two different flow pattern producing two (or more) droplet sizes.
- Future plan:
  - Use numerical simulation
  - Advanced measurement: PIV, 3D-PTV (?)



Thank you

Please visit my poster!

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