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Monodisperse droplet generation for microscale mass transport studies

Christine C. Roberts[1], Rekha R. Rao[2], Anne M. Grillet[1], Carlos F. Jove-Colon[3], Carlton F. Brooks[1], Martin B. Nemer[1]

[1]Thermal and Fluid Experimental Sciences, MS 0345
[2]Thermal and Fluid Processes, MS 0836
[3]Radiological Consequence Management and Response Technologies
Sandia National Laboratories

AICHE Annual Meeting, Minneapolis, MN

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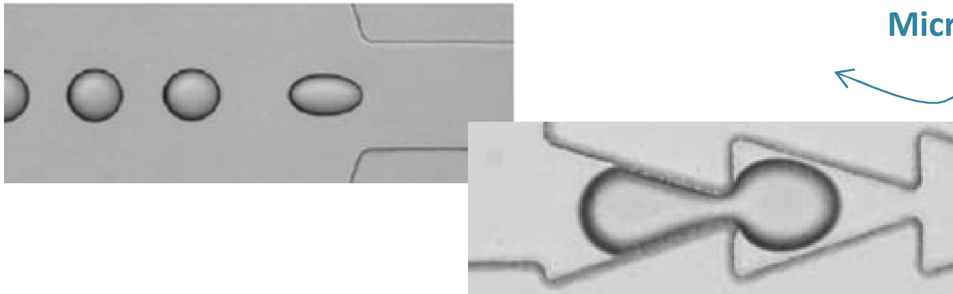
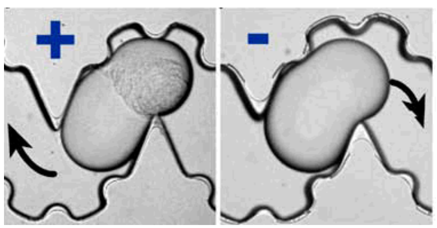
Introduction

- **Microfluidic devices are useful tools for probing liquid-liquid interactions**



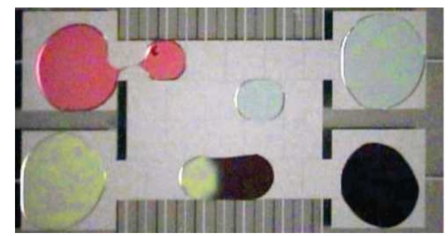
Microfluidic Interfacial Tensometers
Cabral and Hudson, *Lab Chip*, 2006
Liu, Yap, Nguyen, *Phys Rev E*, 2009

- **Understanding liquid-liquid interactions can aid design of microfluidic devices**



Mixing rate affects blood clotting in a microfluidic device
Pompano, *Biophysical Journal*, 2008

Electrowetting moves drops across a channel
Wheeler, *Science*, 2008



Project Outline: Probing mass transfer to drops

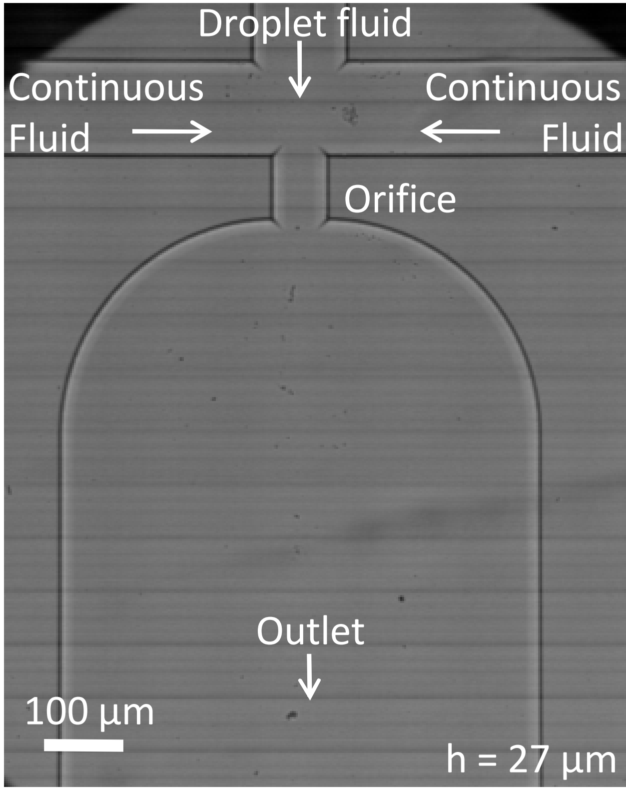
- **Reliable creation of monodisperse drops**
- **Measure and understand the flow field in/around the droplets**
- **Measure and understand species mass transfer to droplets**

Evaluate a thin channel flow-focusing device for the above tasks

Creation of monodisperse droplets

- **Flow focusing device**[1]
  - –Thin channels (w_{or} = 100 µm, h = 27 µm)
  - –Optional OTS coating
- **Fluids studied:**

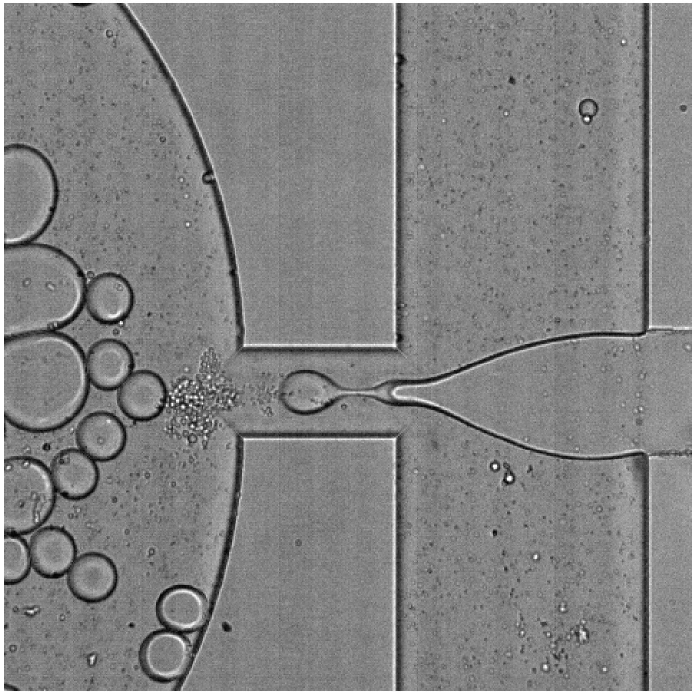
Inner fluid	Outer fluid	$\lambda = \mu_i/\mu_o$
PDMS	Water	9.6 - 96
Water	PDMS	0.05 – 0.1
Water	Dodecane	0.74



- **Image using a high speed Phantom camera**
  - –6000 frames/sec, 8 µs exposure time

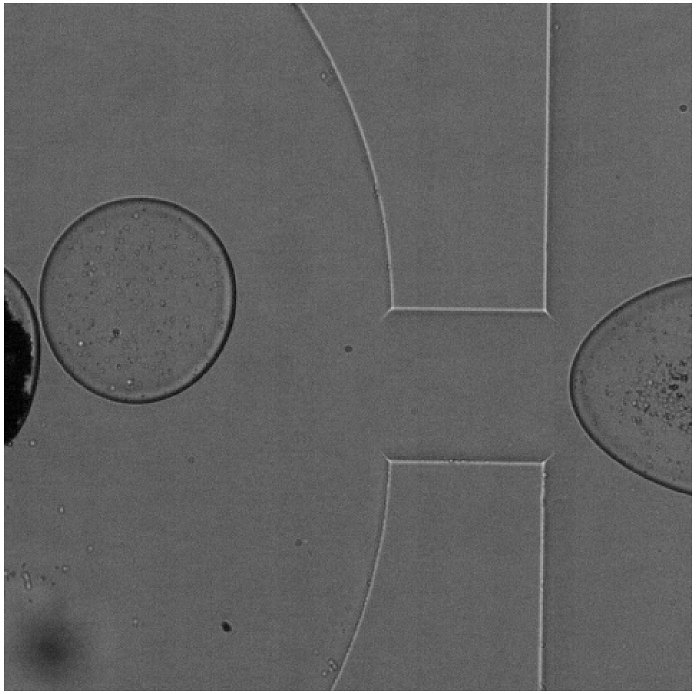
[1]S.L. Anna, N. Bontoux, and H.A. Stone, Appl. Phys. Lett. **82**, 364 (2003).

Creation of monodisperse droplets



20 cst PDMS in water

Q_i = 0.05 mL/hr Q_o = 2 mL/hr
Orifice width = 70 µm
Slowed 200 x



Water in dodecane

Q_i = 0.1 mL/hr Q_o = 0.5 mL/hr
Orifice width = 120 µm
Slowed 200 x

1 µm polystyrene particles added to the water phase to image the flow

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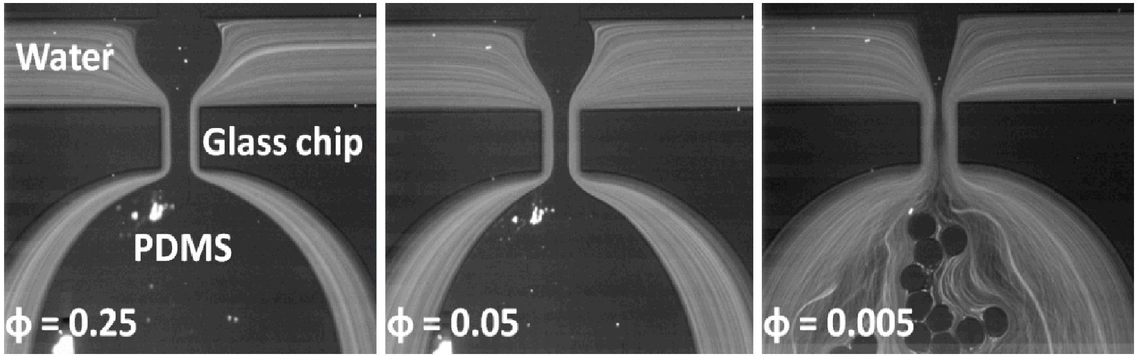
Streaming

Decreasing inner flow rate →



When Q_{drop} / $Q_{continuous}$ gets large, no drops form.

Droplet flow must be unstable in the orifice for breakup

Timescale for viscous thread breakup:

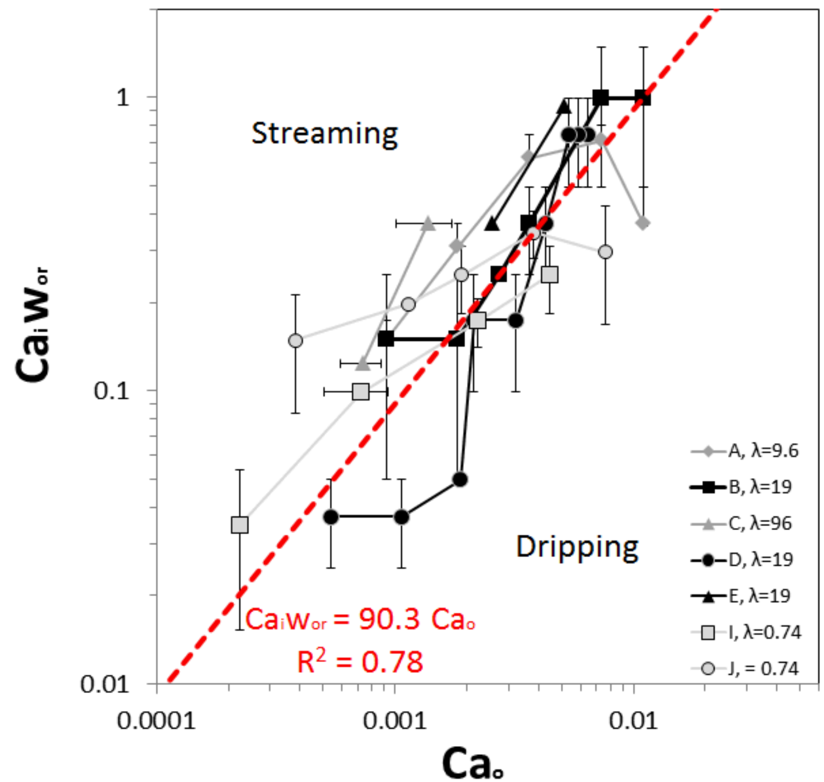
$$t_{vc} \propto \mu_i w_i / \Upsilon Ca_o$$

Timescale in the orifice:

$$t_{or} = L_{or} U_i = L_{or} Q_i / h w_i$$

Condition for breakup:

$$Ca_o \propto \frac{\mu_i Q_i}{\gamma L_{or} h} = \frac{Ca_i w_{or}}{L_{or}}$$



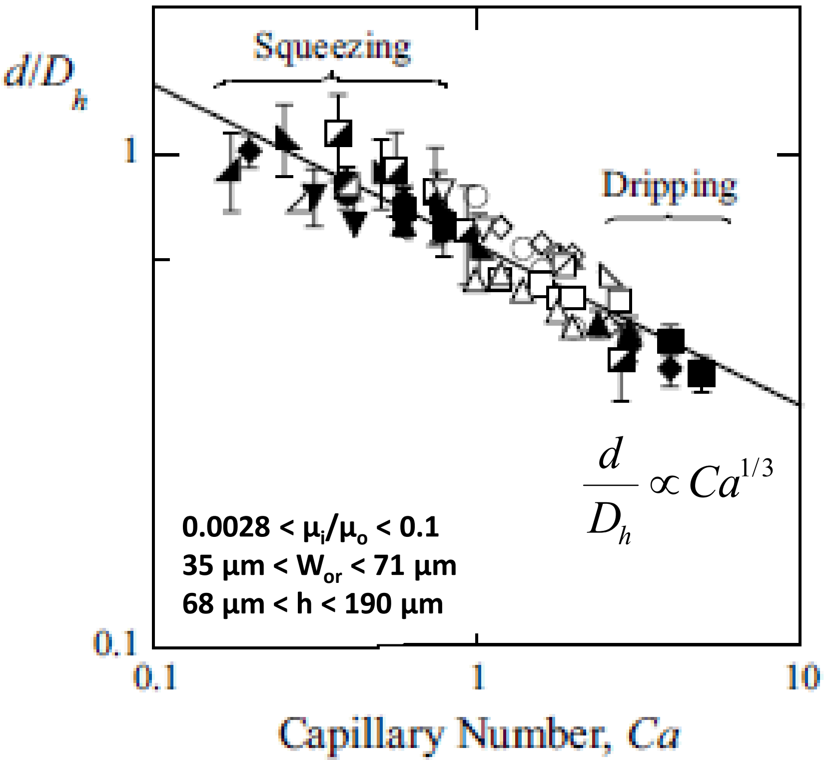
Control of drop size

Water in Oil

Lee, Walker and Anna,
Phys. Fluids, 21, 032103 (2009):

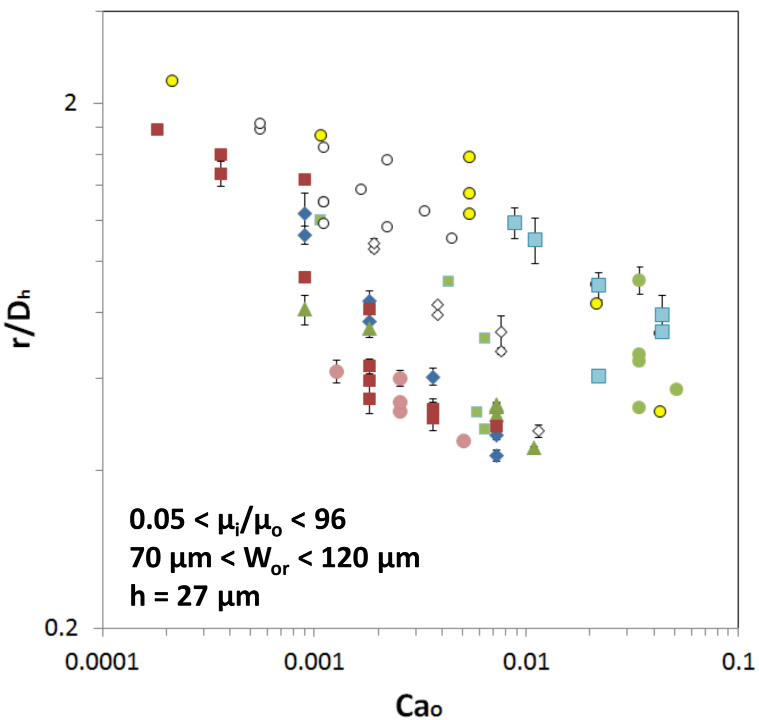
$$Ca_{Anna} = \frac{\mu_c a}{\sigma}\frac{\Delta U}{\Delta z} = \frac{\mu_c a}{\sigma h}\frac{Q_c}{\Delta z}\left(\frac{1}{w_{or}} - \frac{1}{2w_c}\right)$$

$$D_h = \frac{2w_{or}h}{h + w_{or}}$$



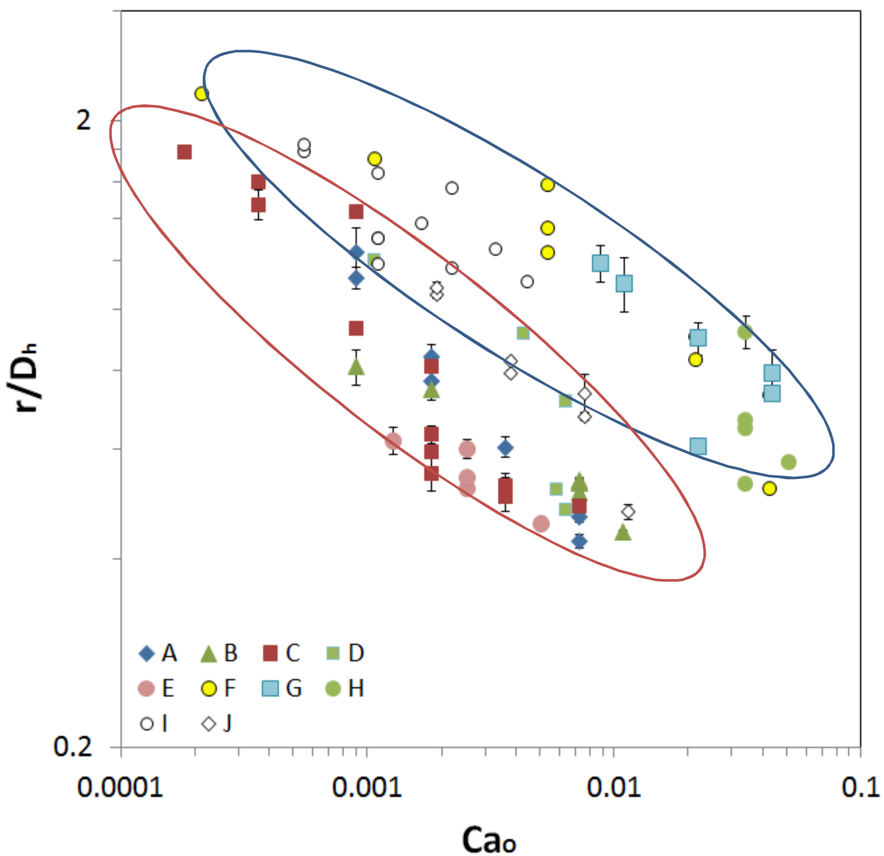
Water in Oil
+
Oil in water

$$Ca_o = \mu_o Q_o / h w_{or} \gamma$$



Control of drop size

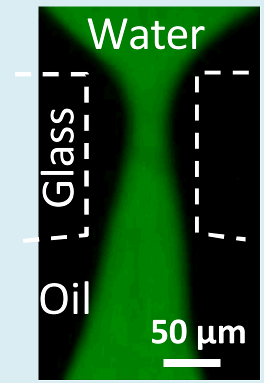
$$Ca_o = {}^{\mu_o Q_o}/_{h w_{or} \gamma}$$



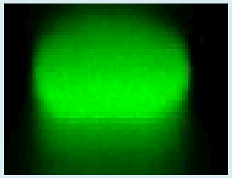
OTS Coated Device

Water in PDMS, $0.05 < \mu_i/\mu_o < 0.1$

Water in Dodecane, $\mu_i/\mu_o = 0.74$



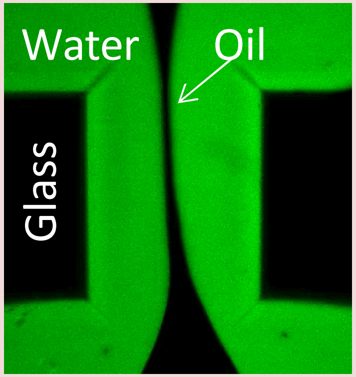
Top View



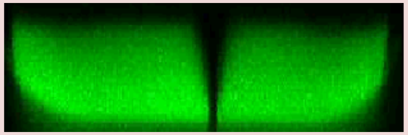
Side View

Non-Coated Device

PDMS in water, $9.6 < \mu_i/\mu_o < 96$

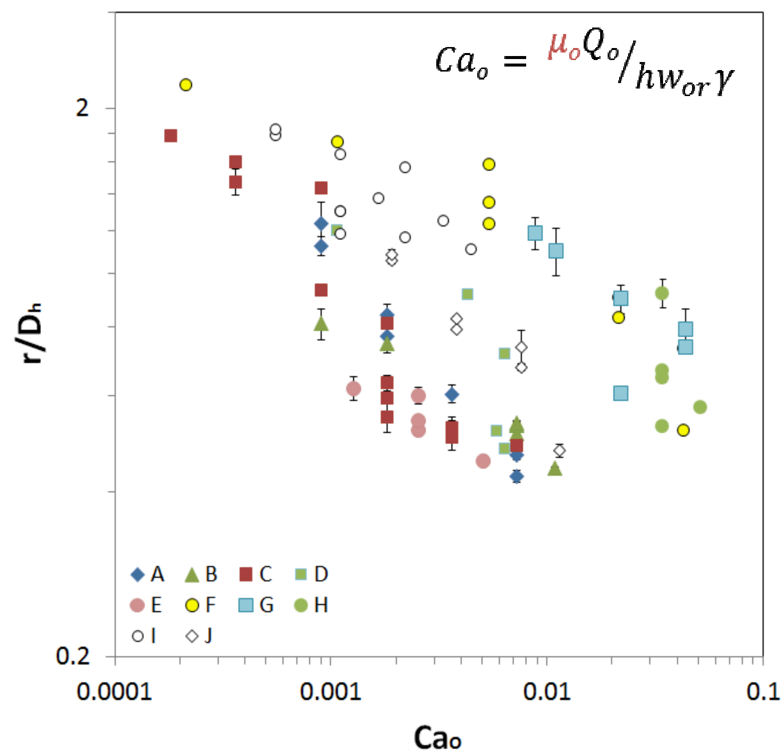


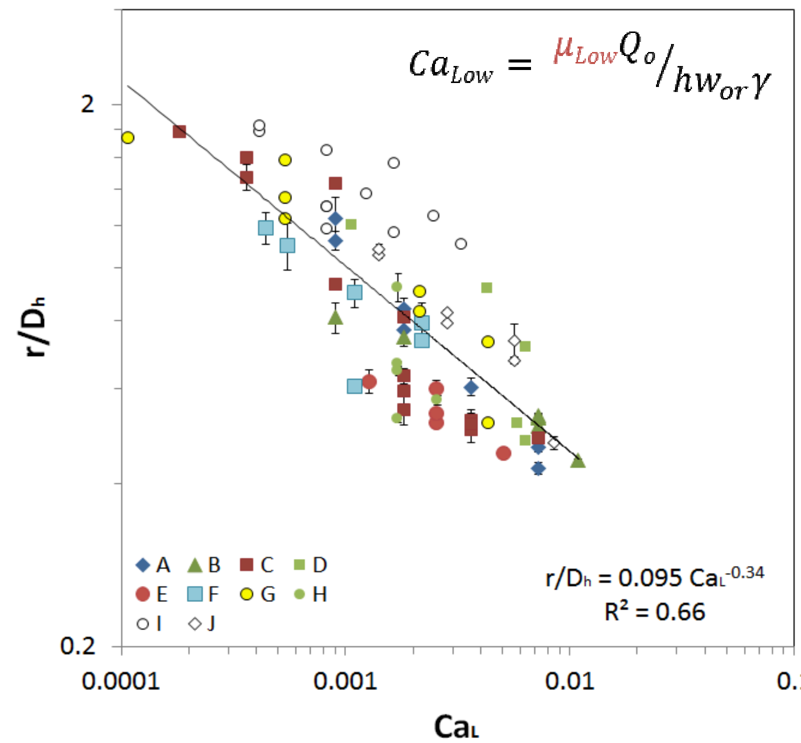
Top View

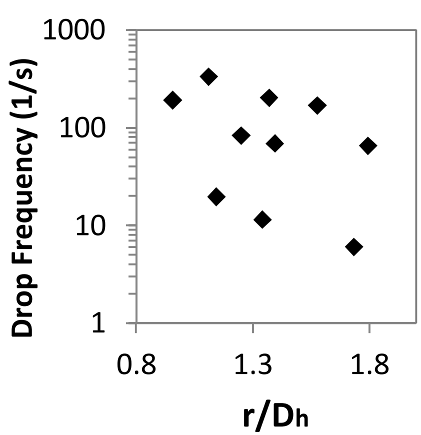


Side View

Control of drop size







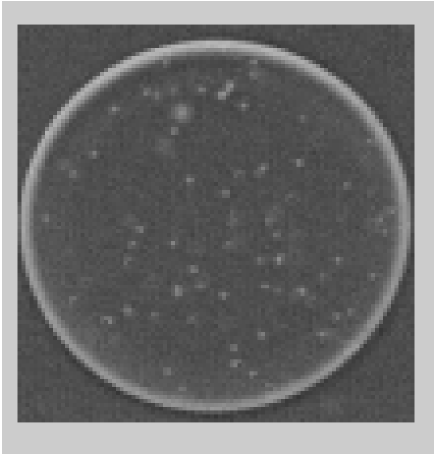
Outer flow rate = control of drop size

Inner flow rate = control of drop spacing

Flow Visualization

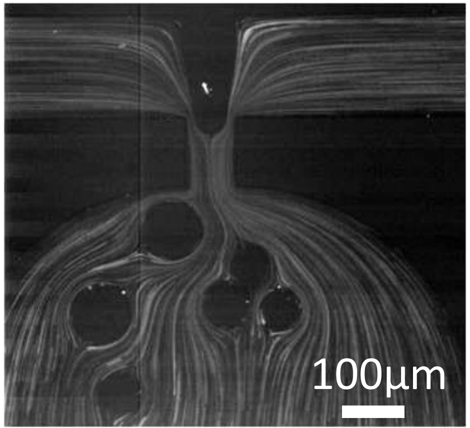
Particles added to the water phase show the flow circulation profile in the droplets

Preliminary results indicate a mobile liquid-liquid interface



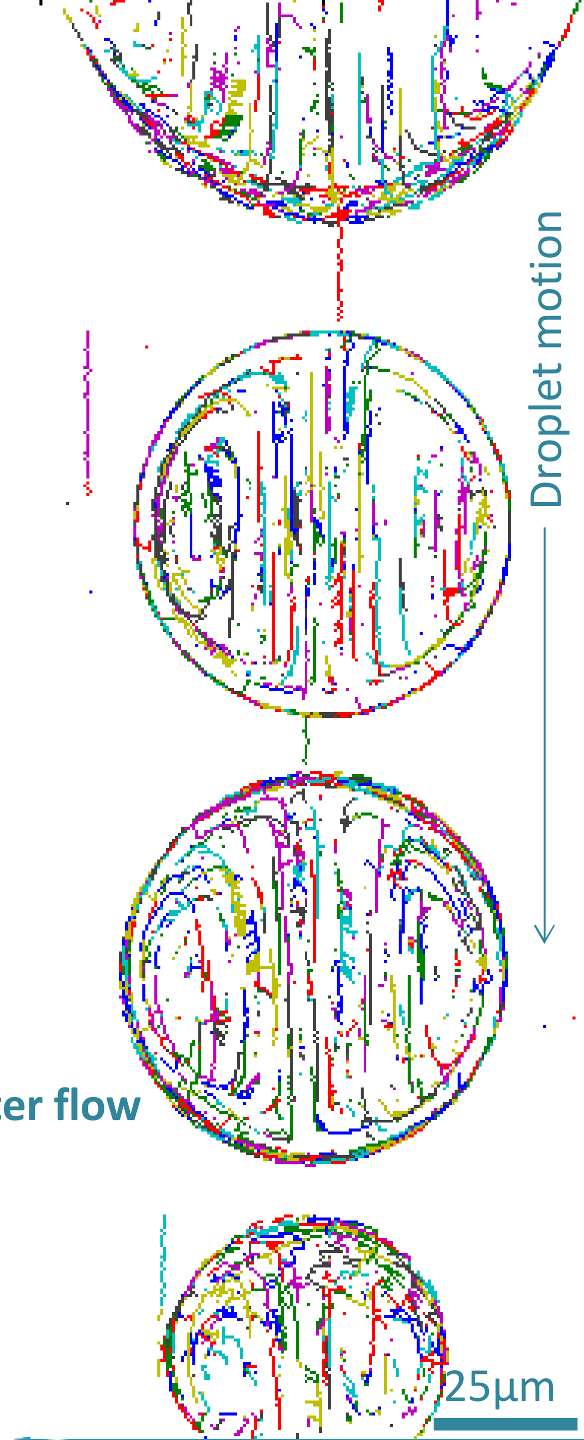
Water in dodecane
Drop frame of reference
Slowed 300x

Drop velocity = V_D
Center streamline velocity / V_D = -2
Edge streamline velocity / V_D = 2.5



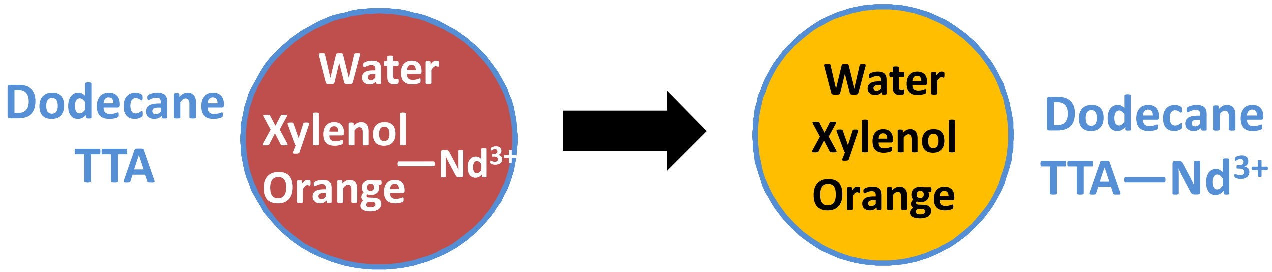
PDMS in water

Also can visualize outer flow

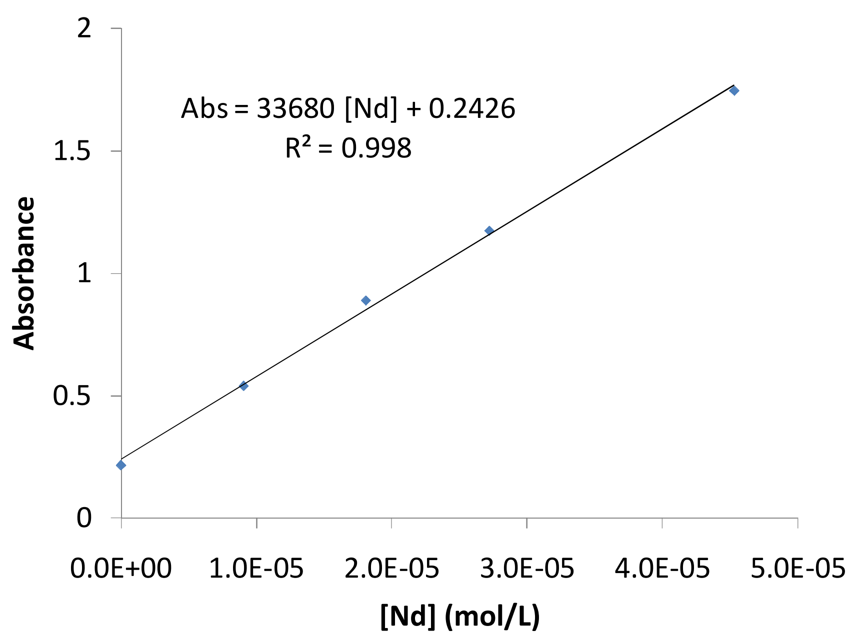


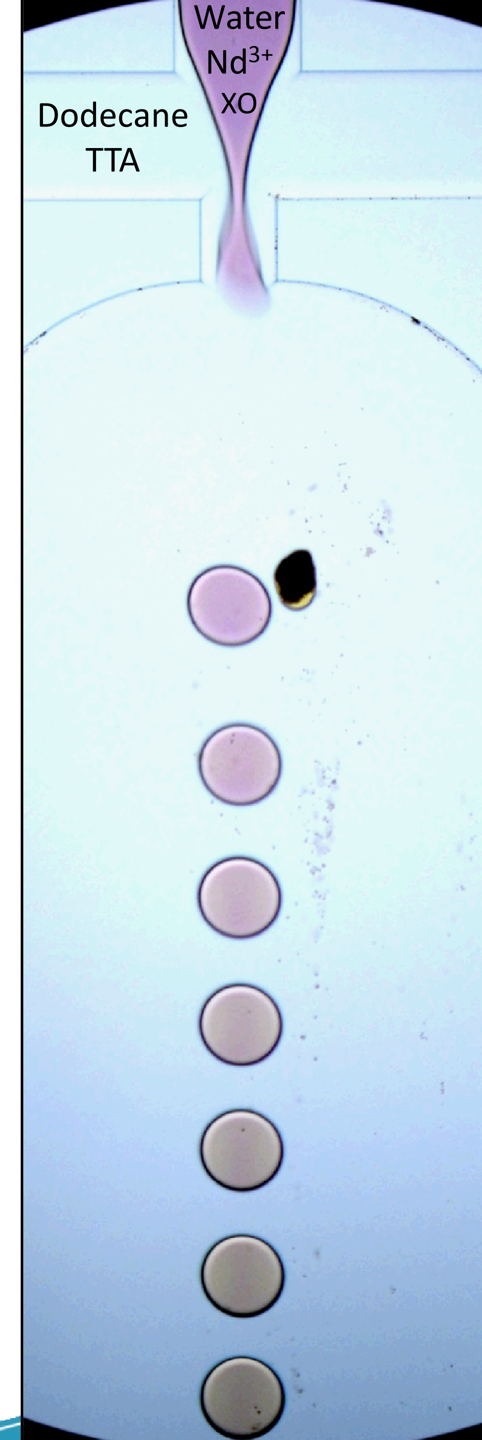
Quantitative Mass Transfer

Model system (buffered pH = 5.5):



Pink (598-609 nm) light absorbance is linear with [Nd]:

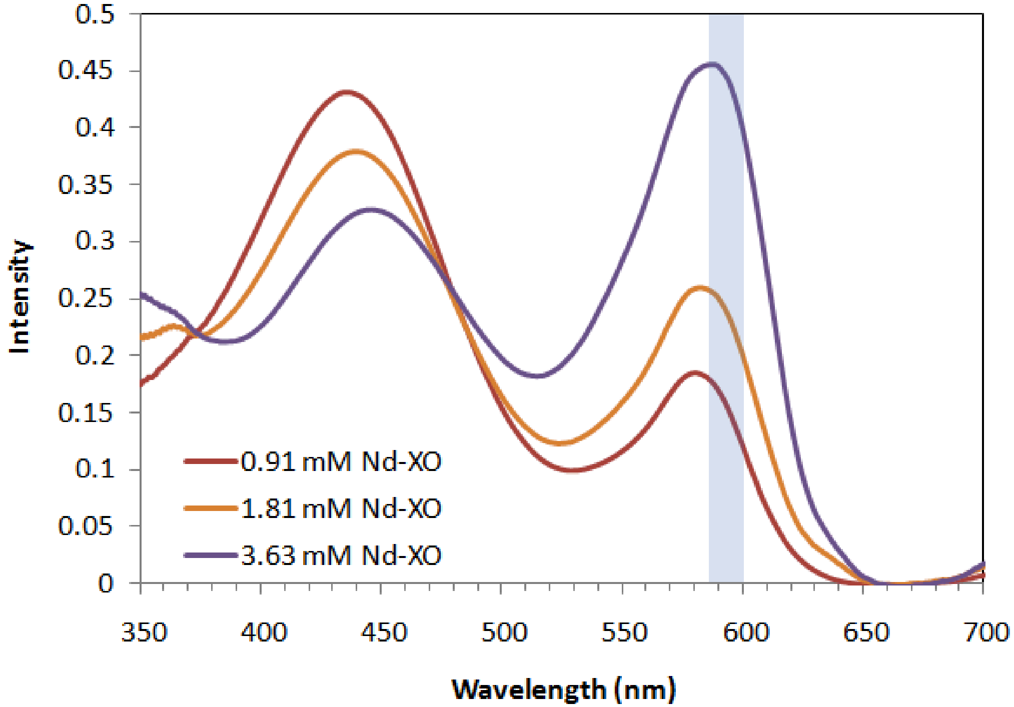


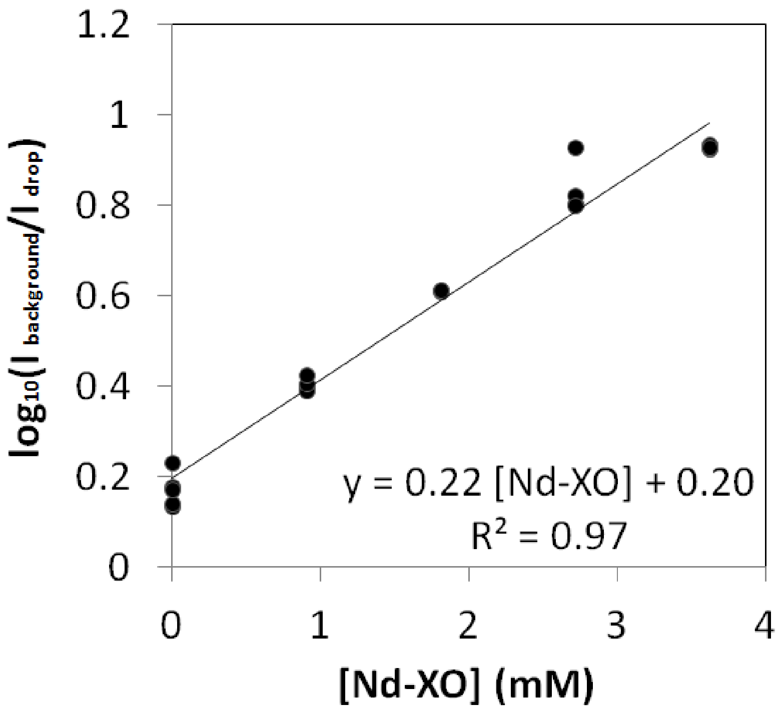


Quantitative Mass Transfer

Bandpass filter

– Only image 590 nm light using Phantom camera

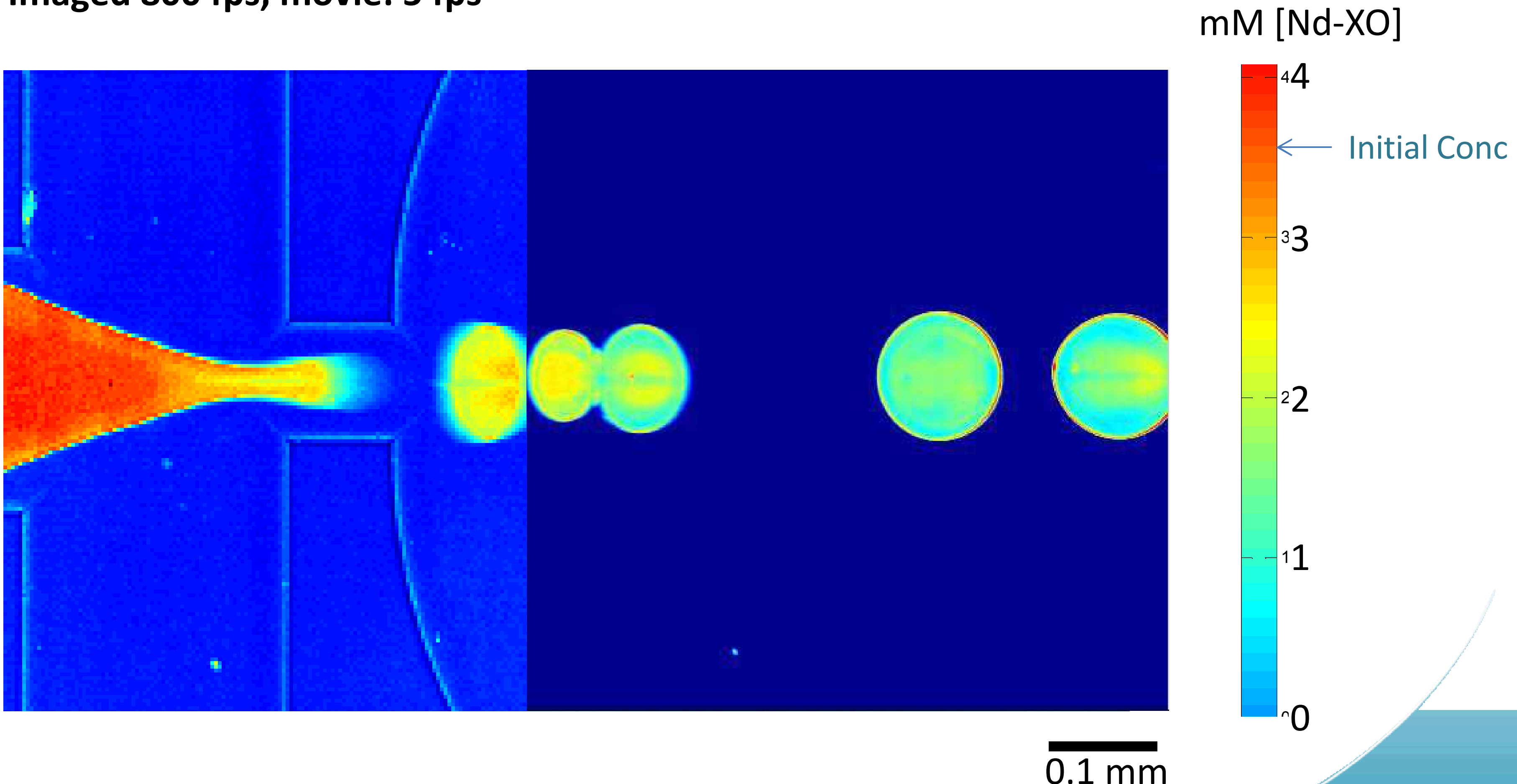




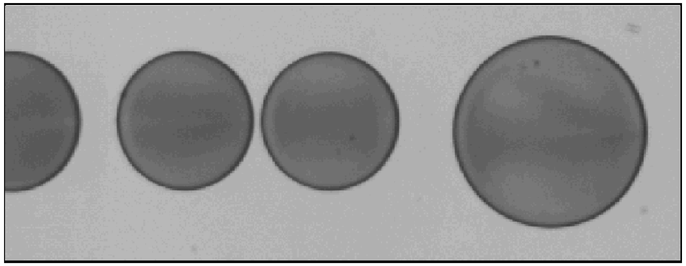
Quantitative Mass Transfer

Continuous flow: 1.5 mL/hr 0.2 M HTTA, 10^{-2} M TBP in dodecane
Droplet flow: 0.5 mL/hr 3.6 mM Nd, 10 mM XO in water

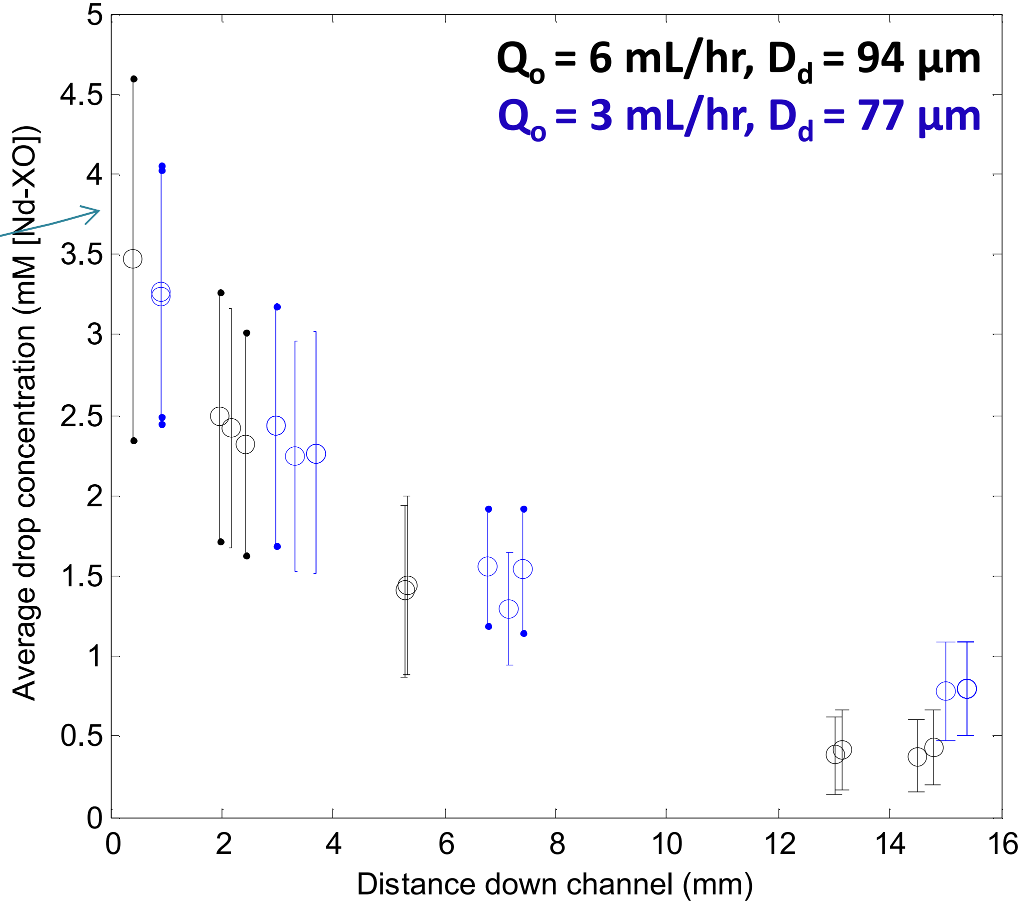
Imaged 800 fps, movie: 5 fps



Mass transfer



Initial [Nd-XO] = 3.6 mM

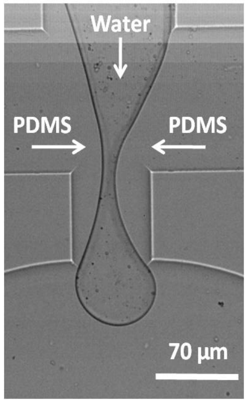


Error bars = standard deviation of concentration in droplet

Conclusions

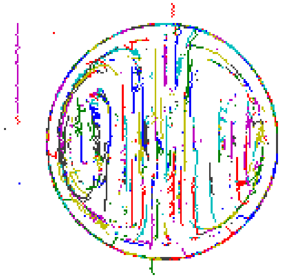
Thin flow-focusing devices create monodisperse emulsions

- Independent control of droplet size, frequency
- Better understand Ca_{Low}



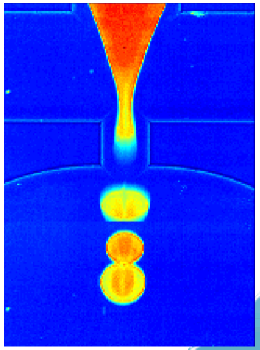
"Simple" flow field in/outside of drops can be measured using particle tracking

- How do surface active species influence the droplet flow?



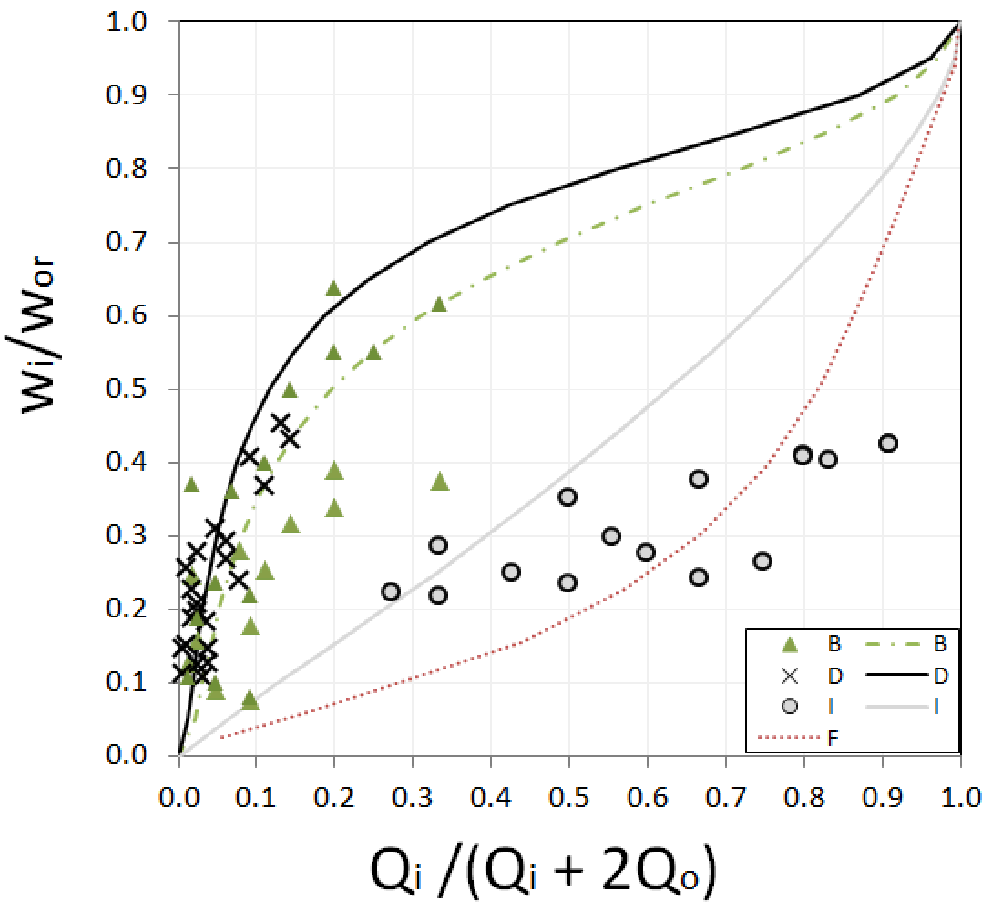
Mass transfer can be quantitatively imaged

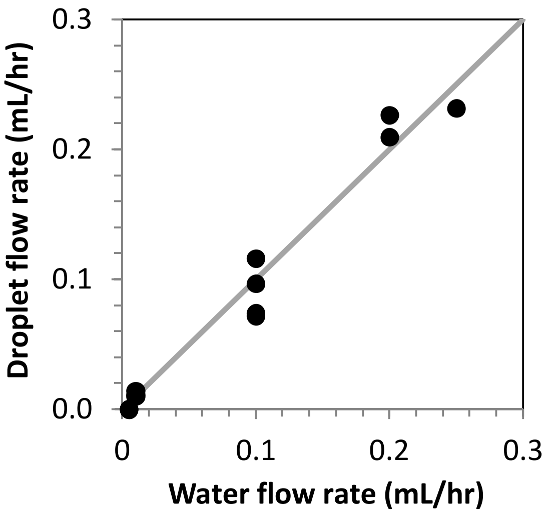
- Thin channels simplify image analysis

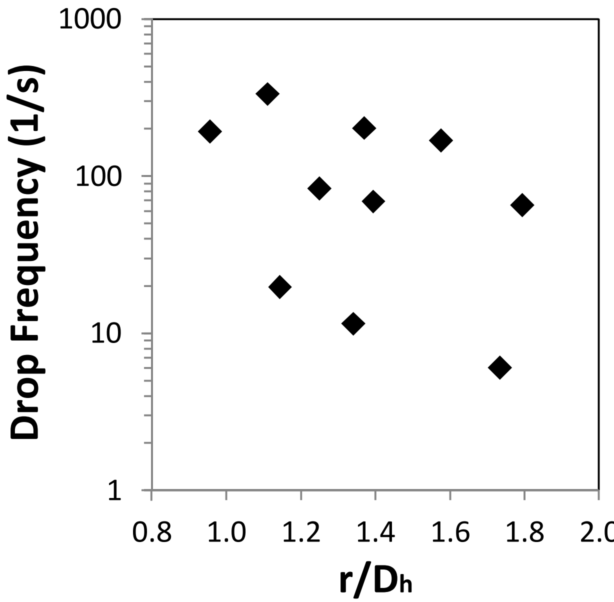


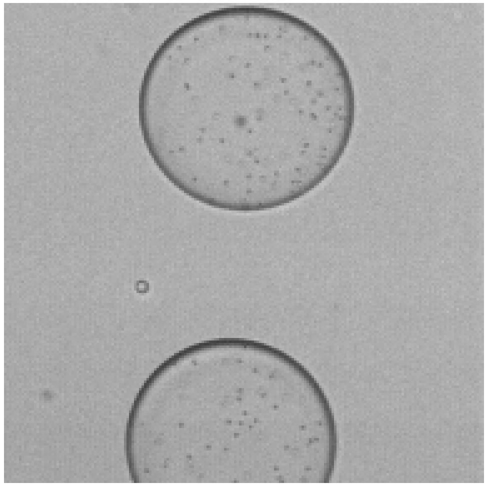
Backup Slides

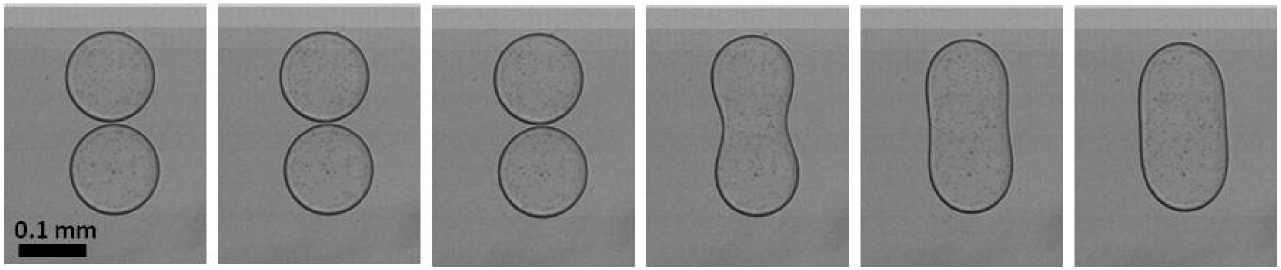
Streaming: Inner flow width





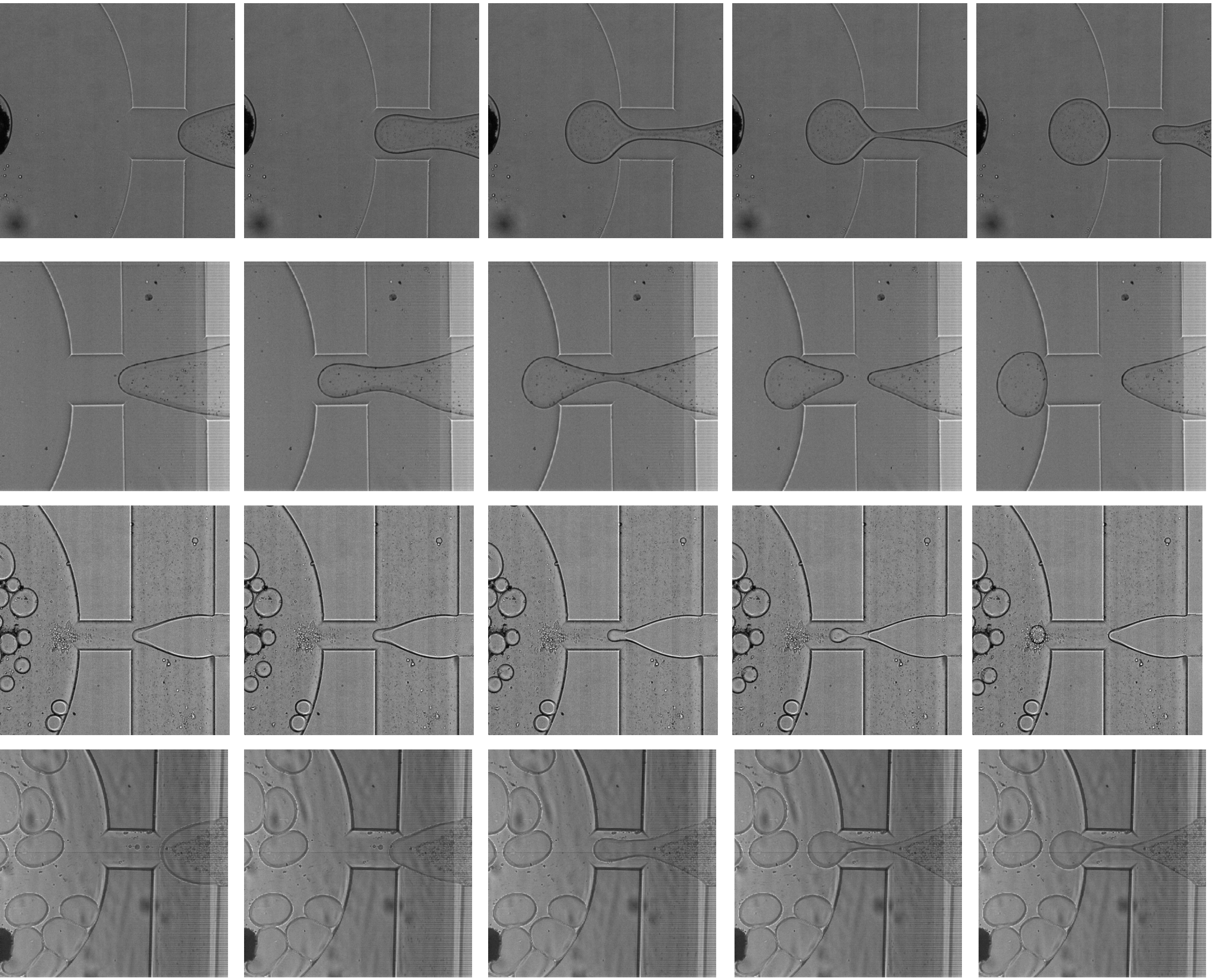






Coalescence of water droplets in dodecane (Case I) . Q_i = 0.01 mL/hr, Q_o = 0.5 mL/hr. The time between frames is 0.16 ms.

Case	Inner fluid	ν_i (cSt)	Outer fluid	ν_o (cSt)	λ	σ (mN/m)	w_{or} (µm)	2a (µm)	Δz (µm)	h (µm)
A	PDMS	10	water	1	9.6	40	70	100	200	27
B	PDMS	20	water	1	19	40	70	100	200	27
C	PDMS	100	water	1	96	40	70	100	200	27
D	PDMS	20	water	1	19	40	120	200	200	27
E	PDMS	20	water	1	19	40	100	100	200	27
F	water	1	PDMS	10	0.1	40	120	200	200	27
G	water	1	PDMS	20	0.05	40	120	200	200	27
H	water	1	PDMS	20	0.05	40	70	100	200	27
I	water	1	dodecane	1.8	0.74	52	120	200	200	27
J	water	1	dodecane	1.8	0.74	52	70	200	200	27



Water in dodecane
Wor = 120 um
0.01, 0.5

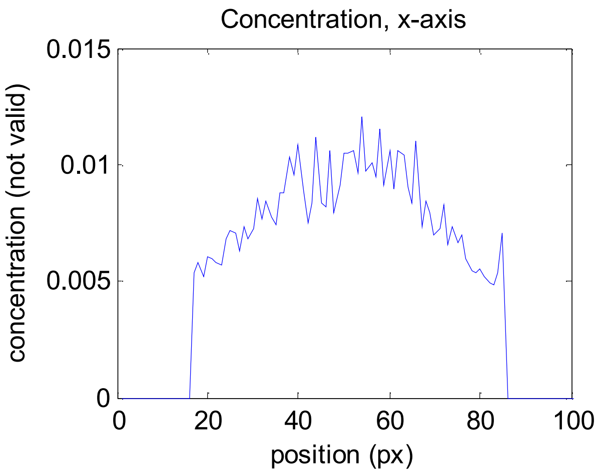
Water in 10 cst PDMS
Wor = 120 um
0.25, 0.1

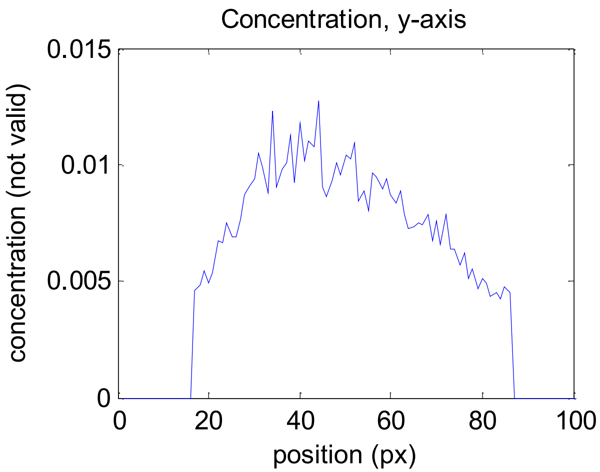
10 cst PDMS in water
Wor = 70 um
2, 0.01

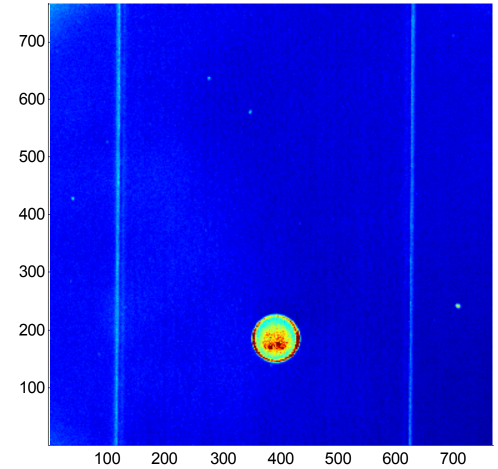
20 cst PDMS in water
Wor = 120 um
1, 0.005

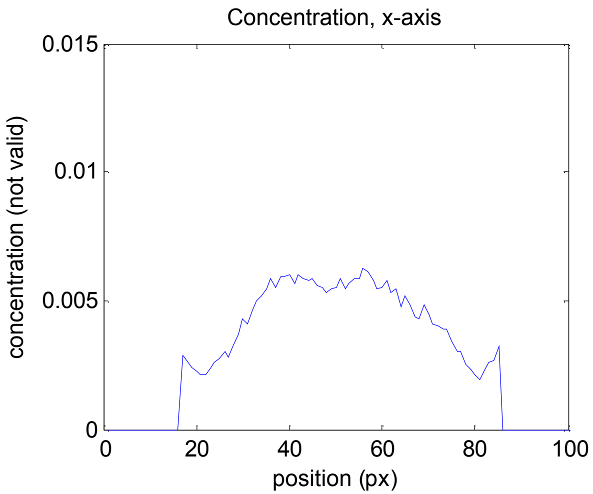
“Concentration” in a drop

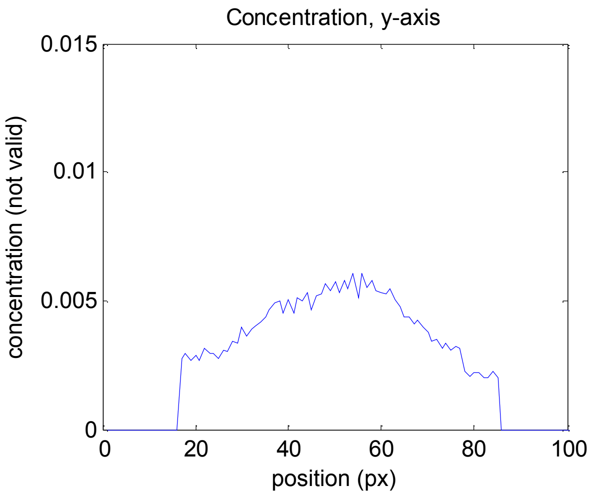
4 mL/hr, 0.1 mL/hr

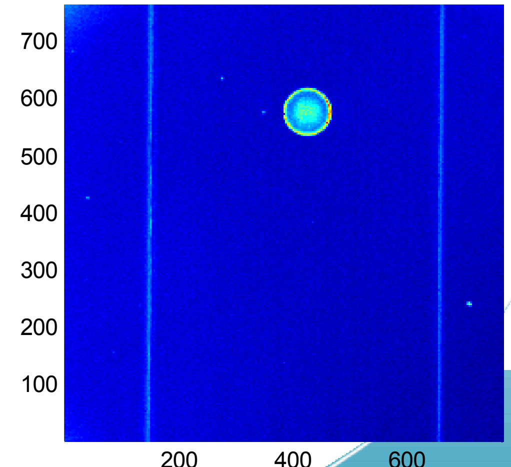












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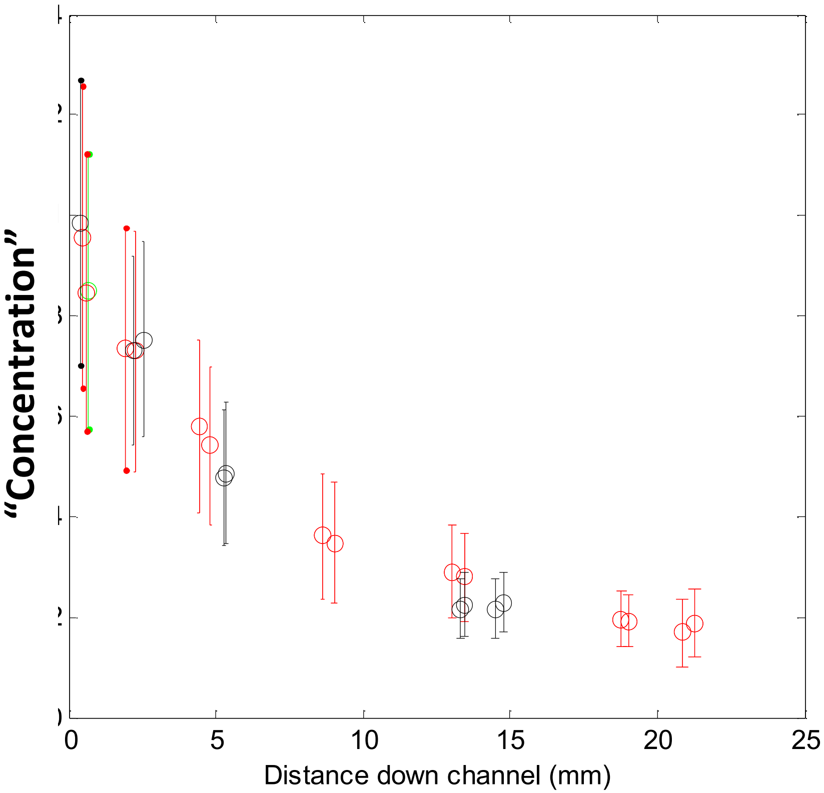
“Concentration” down the channel

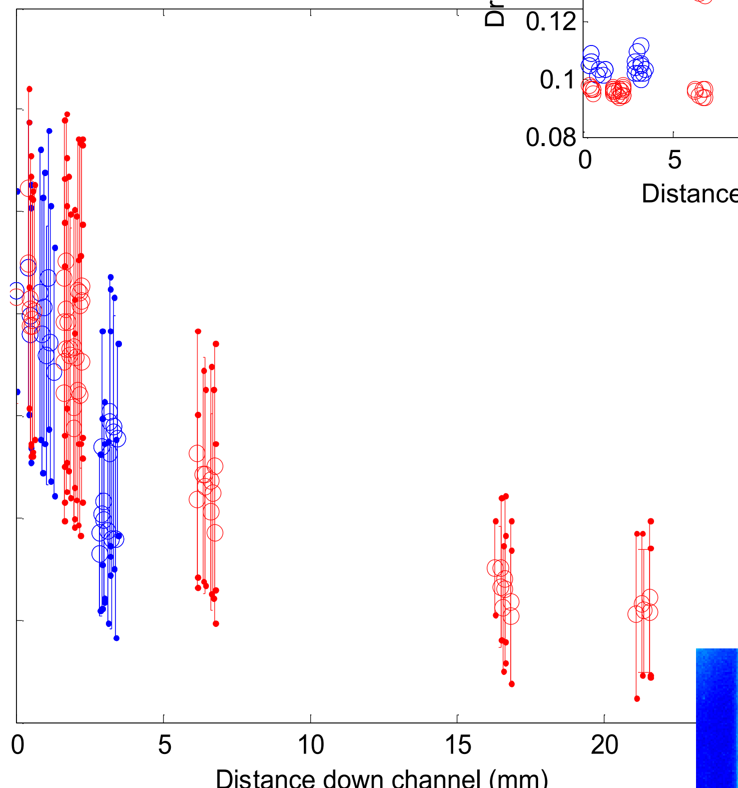
No coalescence

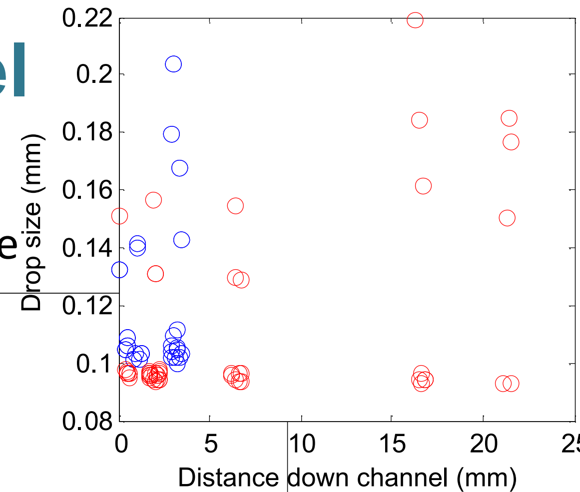


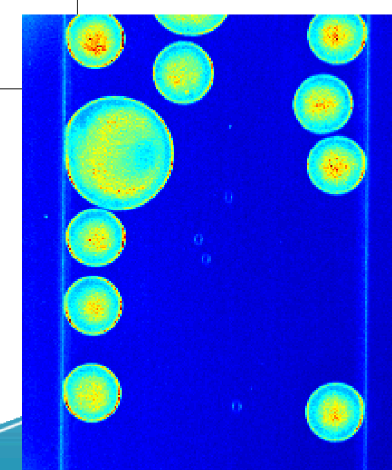
4 mL/hr, 0.1 mL/hr

3 mL/hr, 0.1 mL/hr

Coalescence







4 mL/hr, 0.5 mL/hr

4mL/hr, 1 mL/hr

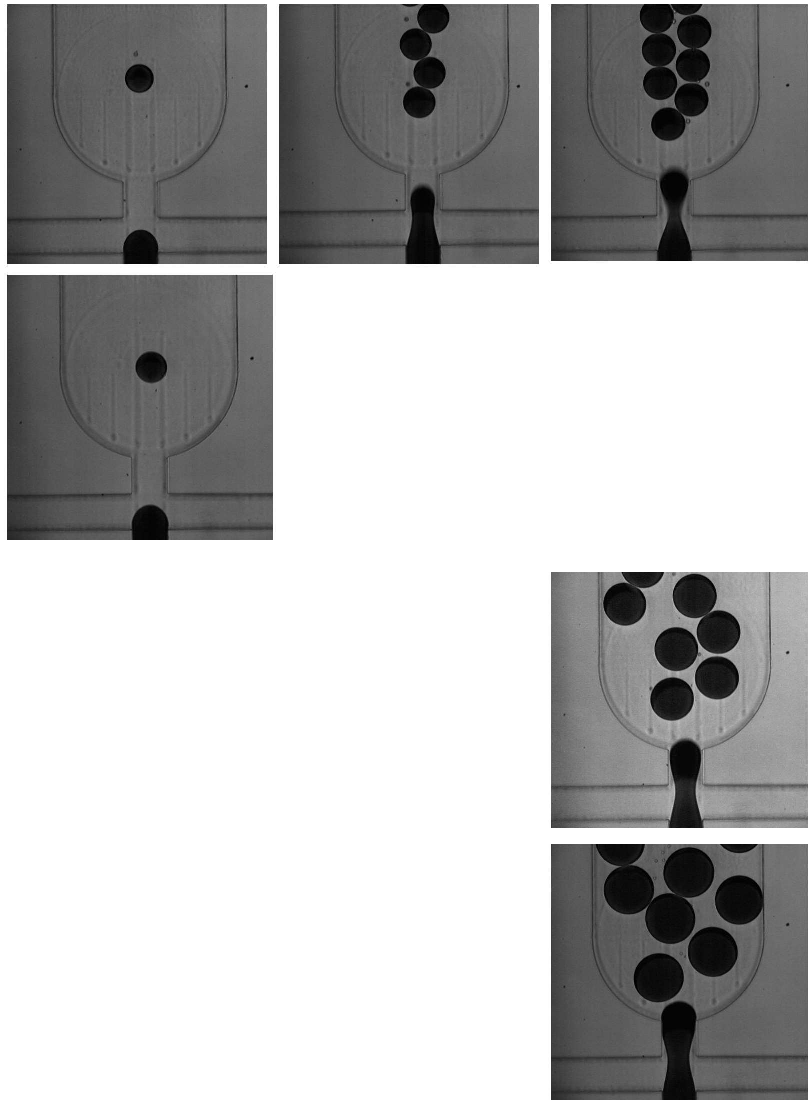
Q_i = 0.1 mL/hr | 0.5 mL/hr | 1 mL/hr

Q_o = 4 mL/hr

3 mL/hr

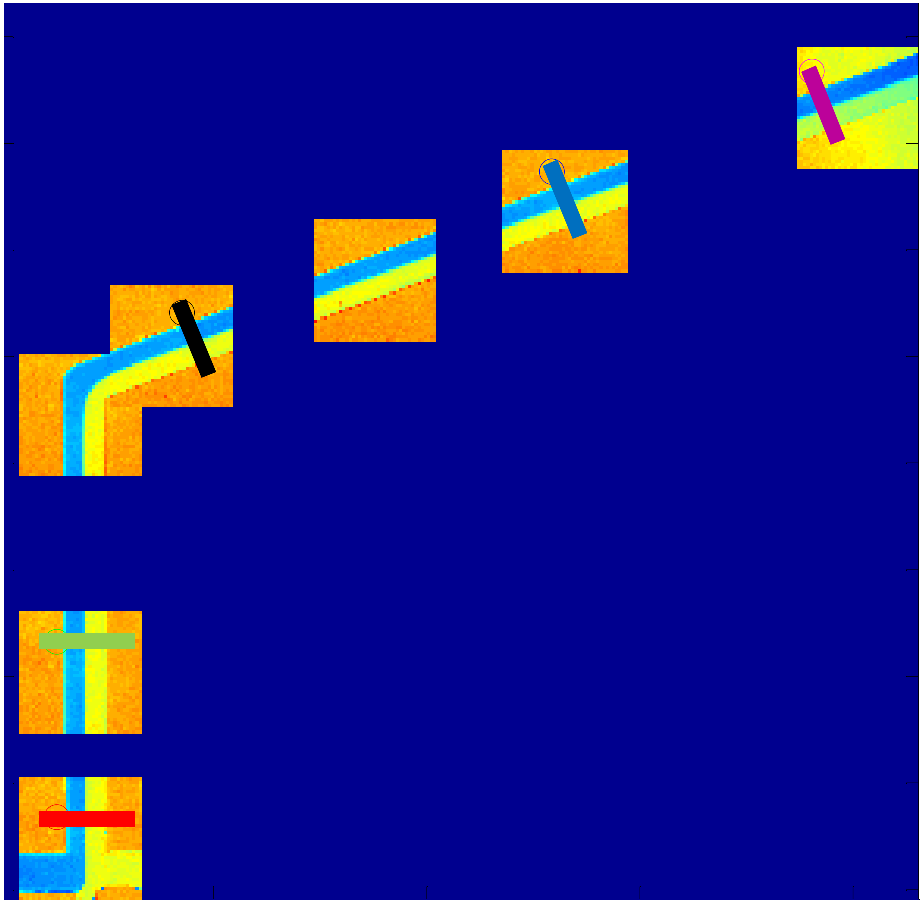
2 mL/hr

1 mL/hr



Diffusion Coefficients: Nd-XO in Water

Next to each other in inlet channel:
0.5 mL/hr pure water
0.5 mL/hr water + Nd-XO



Concentration analyzed over 5 cross sections, various distances down channel