Extending the Digital Microfluidics Process to Form Emulsions Using Low-Surface-Energy Fluids

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22nd Target Fabrication Meeting
Las Vegas, NV
12–16 March 2017
Summary

The process of forming and assembling individual fluid droplets into emulsions using electric fields has been demonstrated.

- The electrical requirements and electrode designs for forming droplets of the right size for making OMEGA and National Ignition Facility (NIF)-size targets and combining them to form emulsions were determined.
  - Water-in-oil and oil-in-water + surfactant emulsions were both formed and transported.
- Demonstrated how to overcome liquid pinning and capillary forces to move droplets (including low-surface-tension fluids) from a narrowly spaced parallel-plate electrode design to a wider separation for dielectrophoresis (DEP) centering.
- Future work will be to add a polystyrene monomer and photoinitiator to the oil phase to make a polystyrene shell.
Electric-field–based microfluidics can be used to form, transport, and center oil-water emulsions

- Each step is programmable
- Can work with a wide range of droplet sizes (0.01 to 12 \( \mu\)L) (OMEGA and NIF shells)
Transforming the double emulsion into a spherical concentric shell using an electric field limits the liquids that can be used.

- $\kappa_2 > \kappa_1$ is needed for the DEP force to center the inner droplet (to minimize the total energy)

- Polystyrene shells
  - Water – fluorobenzene – hexylene or decane
    $(\kappa = 78)$ $(\kappa = 4.8)$ $(\kappa = 2.0)$ $(\kappa = 2.2)$
    - DEP force for a 1-$\mu$m offset is 0.24 nN
      (OMEGA shell)

- Resorcinol-formaldehyde (RF) shells
  - Mineral oil – water – silicone oil
    $(\kappa = 2.2)$ $(\kappa = 78)$ $(\kappa = 2.6)$
    - DEP force for a 1-$\mu$m offset is 32.5 nN
An OMEGA-size water-in-oil emulsion was formed and transported.

- To make polystyrene shells
  - Forming a water-in-oil emulsion (sped up to 4× faster)
  - Transporting the emulsion (sped up to 3× faster)

Decane
- \(424 \, V_{\text{rms}}\)
- 100 Hz
- (0.18 \(\mu\)L)

Water
- \(88 \, V_{\text{rms}}\)
- 100 Hz
- (5 \(\mu\)L)

Water-in-oil emulsion
- (0.360 and 0.025 \(\mu\)L)

2 mm
- (30-\(\mu\)m spacing)
Forming *oil-in-water* emulsions requires a surfactant to be added to the water phase, which complicates the droplet dispensing process.

- To make RF shells

**Water**
100 $V_{\text{rms}}$, 100 Hz  
(real time)

**Silwet L-77/water (1× CMC)**
75 $V_{\text{rms}}$, 10 kHz  
(spéd up to 3× faster)

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$12 \text{ mm} \ - 6 \text{ mm}$

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**Top view**

**Side view of electrode used to form the droplet**

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CMC = critical micelle concentration
Heating the membrane generates a thermocapillary pressure wave that ruptures the surfactant-loaded membrane to form the droplet.

Without heating, the membrane of a 1× CMC solution takes ~3 min to rupture at 100 \( V_{\text{rms}} \).
The membrane ruptures in a manner that is representative of the Rayleigh–Plateau instability

- 5× CMC
- 270-μm spacing
- 6.5 W

When heat is applied
- A wave-like instability pattern develops along the length of the membrane at \( t < 0.17 \) s
- Amplitude of the oscillations grows with time
- The membrane ruptures simultaneously along its length, forming individual droplets
NIF-size oil-in-water emulsions containing a surfactant were formed and transported.

Forming the oil-in-water emulsion (sped up to 6× faster)

Transporting the emulsion (sped up to 9× faster)

Mineral oil (610 $V_{rms}$, 100 Hz)

Water + surfactant (5× CMC) (75 $V_{rms}$, 10 kHz)

Oil-in-water emulsion (0.71 and 0.66 $\mu$L)
Changing the shape of the electrodes and the sequencing of the voltage allows low-surface-energy emulsions to be more-easily transported.

- Rectangular electrodes (10 × 2.5 × 0.18 mm)
  - 6.6-μL mineral oil and 5× CMC water emulsion
  - 75 V_{rms} 10 kHz

(Sped up to 4× faster)
Current work is to move the “pancake”-shaped emulsion to a wider-spaced electrode to form the spherical target

- A three-dimensional profile allows gravity to supplement the electric forces to overcome pinning at acute interfaces and capillary forces.

5× CMC-water 10-μL droplet
45° tilt angle, 75 V_{rms}, 10 kHz

(Sped up to 4× faster)
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  - Water-in-oil and oil-in-water + surfactant emulsions were both formed and transported.
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