Introduction: Making Emulsions

* Crucial elements for making emulsions:
  - Two immiscible liquids such as oil and water
  - Emulsifying agent (surfactant): SDS (sodium dodecyl sulfate), lipids
  - Mechanical force for mixing and dispersing (kinetically stable)

Parameters: droplet volume fraction; surfactant type; applied stress

* Examples of food emulsions:
  Butter (W/O); Mayonnaise (O/W); Salad dressing (O/W)
Shear Oscillation Light Scattering of Concentrated Emulsions

Jung-Ren Huang (黃仲仁) \(^{1,2}\) & Thomas G. Mason \(^{1,3}\)

\(^1\) Department of Physics, NTNU
\(^2\) Department of Chemistry and Biochemistry, UCLA
\(^3\) Department of Physics and Astronomy, UCLA

Deformable colloids: emulsion droplets
\(\phi > \phi_g \approx 0.58, \quad \phi > \phi_{MRJ} \approx 0.64\)

Phase-resolved (time-resolved) shear oscillation light scattering
droplet deformation ↔ structure


\((\text{NCTU IOP, Jan 6, 2011})\)
Outline

• Experiment: Materials and Shear Oscillation Light Scattering Setup
  – A Complex System of Multiple Degrees of Freedom
  – Phase-Dependent Primary and Secondary Bragg spots

• Droplet Deformation in Concentrated Emulsions
  – Three Scattering Intensity Anisotropy Factors and Tilt Ellipsoid Model

• Shear-Induced Restructuring: Ordering and Disordering
  – Soft Jamming, Sliding HCP Layer, and Shear Melting Regimes
  – Shear-History Dependence of Emulsion Structure

• A Simple, Intuitive Model (Mechanism)
  – A Simple Story for a Complex System
**Materials: O/W Emulsion**

- **Dispersed phase:** PDMS; 350 cP
  - Silicone oil, polydimethylsiloxane (PDMS)
- **Continuous phase:** NP-7/water @ 40wt%; 600±30 cP
  - Nonionic Surfactant: Tergitol@ NP-7
    (Nonylphenol Ethoxylate)
    \[ C_{9}H_{19}-(\text{O})-(\text{OC}_{2}H_{4})_{7} -\text{OH} \]
    221 cP @ 25°C

**Experiment @ 22±1°C**
- Oil volume fractions: \( \phi = 0.55 \sim 0.75 \)
- Droplet size:
  - Initially polydisperse, diameter > 10 \( \mu \)m
  - Shear-rupturing
  - Monodisperse, diameter \( \approx 2.2 \) \( \mu \)m
  - Shear-induced ordering and disordering

*** Matching refractive indices \( \approx 1.40 \)
*** \( \sigma \approx 2 \) dyne/cm

Introduction: Making Emulsions

* Crucial elements for making emulsions:
  - Two immiscible liquids such as oil and water
  - Emulsifying agent (surfactant): SDS (sodium dodecyl sulfate), lipids
  - Mechanical force for mixing and dispersing (kinetically stable)

Parameters: droplet volume fraction; surfactant type; applied stress

* Examples of food emulsions:
  - Butter (W/O); Mayonnaise (O/W); Salad dressing (O/W)
Shear Oscillation Light Scattering Apparatus

**Side view:**

Camera @ ≤ 30fps

**Top view:**

Shear strain $\gamma = \gamma_{\text{max}} \sin \psi$; $\psi = 2\pi ft$; $30 \leq \gamma_{\text{max}} \leq 100$; $f \leq 5 \text{ Hz}$.

Control: emulsion $\phi$; shear conditions: $\gamma_{\text{max}}, f$; $\dot{\gamma}_{\text{max}} = 2\pi f \gamma_{\text{max}}$
Time-Resolved Scattering Patterns

Recorded @ 30FPS; played @ 15FPS
Big Questions

Important factors to consider:

* droplet volume fraction $\phi \geq 0.55 \leftrightarrow$ inter-droplet interaction
  $\leftrightarrow$ droplet deformation $\leftrightarrow$ emulsion structure

* Shear conditions: $\gamma_{\text{max}}$ and $f$ for glassy emulsions

\[ \phi \text{ of emulsion; } (\gamma_{\text{max}}, f) \text{ and } \psi \text{ of shear oscillation} \]

\[ \gamma = \gamma_{\text{max}} \sin \psi \]

\[ \psi = 2\pi f t \]

Droplet Deformation $\leftrightarrow$ Emulsion Structure

Analysis of time-resolved scattering patterns
A Brief History: Droplet Deformation under Shear

- Deformation of isolated droplets subjected to shear flows
  G. I. Taylor (1934); S. Torza, et al. (1972); J. Vermant, et al. (1998); …

- Shear-induced deformation of concentrated droplets
A Brief History:
Shear-induced Restructuring

• Shear-induced restructuring of hard colloidal spheres
  R. L. Hoffman (1972); B. J. Ackerson & N. A. Clark (1981);
  M. K. Chow & C. F. Zukoski (1995); …

* Shear ordering of hard spheres: $\phi < \phi_g$ for $\gamma > 1$; $\phi >, =, < \phi_g$ for $\gamma_{\text{max}} < 1$.

Hard sphere systems

Equilibrium phases

Fluid

Crystal: HCP/FCC

Non-equilibrium states

Glassy behavior due to caging

Jamming and Un-jamming of Concentrated Droplets of Uniform Size

\( \phi > \phi_{MRJ} \approx 0.64 \)

- Hard Spheres: \( \phi \leq 0.74 \)
  - Initially ordered spheres
  - Maximum \( \gamma < 1 \).
    - Spheres jammed.

- Deformable Droplets: \( \phi \leq 0.74 \)
  - Initially ordered droplets
  - Yielding
  - Unlimited \( \gamma \).
    - Droplets not jammed.
    - (Droplets deform.)

* Effect of large-\( \gamma \) shear on interaction, structure, deformation?
Shear-Ordering of Hard Colloidal Spheres

Shear directions

He-Ne laser // Z-axis

$\Delta z = 100 \, \mu m$

Droplet diameter $\approx 2.2 \, \mu m$

$\approx 50$ layers of sliding HCP droplets

BJ Ackerson, J. Rheol. 34, 553 (1990)
Symmetries of the System

- **Mirror symmetry about \( q_x \):**
  \[
  I(R_1) = I(R_2); \quad I(L_1) = I(L_2); \quad I(M_1) = I(M_2);
  \]
  \[
  I(mr_1) = I(mr_2); \quad I(ml_1) = I(ml_2)
  \]

- **Left-Right symmetry:**
  \[
  I_{RP}(\dot{\gamma}) = I_{LP}(-\dot{\gamma}); \quad I_R(\psi) = I_L(\psi+\pi)
  \]
  \[
  I_{rp}(\dot{\gamma}) = I_{lp}(-\dot{\gamma}); \quad I_r(\psi) = I_l(\psi+\pi)
  \]
Shear Oscillation Light Scattering (SOLS)

- Primary Bragg spots: \( \phi = 0.70; \ \gamma_{\text{max}} = 100; \ f = 0.5 \text{ Hz.} \)

**Diagram:**
- Avg. peak intensity of \( L_1 \) and \( L_2 \)
- Avg. peak intensity of \( R_1 \) and \( R_2 \)
- Phase \( \psi \)
- Shear direction

**Additional Information:**
- Played real time recorded @ 30 fps

*References*
Shear Oscillation Light Scattering (SOLS)

- Scattering pattern movie:

\[ \phi = 0.70; \gamma_{\text{max}} = 100; f = 0.5 \text{ Hz.} \]

\[ I_{mlp} \downarrow I_{mrp} \]

\[ I_{lp} \rightarrow \]

\[ I_{rp} \leftarrow \]

recorded @ 30 fps
played 1/2X real time

Phase-Resolved Peak Intensities

- Primary Bragg spots: \( \phi = 0.70; \gamma_{\text{max}} = 100; f = 0.5 \text{ Hz.} \)

\[ \gamma = \gamma_{\text{max}} \sin \psi = \sin(2\pi ft). \]

\[ \dot{\gamma}_{\text{max}} \equiv 2\pi \gamma_{\text{max}} f = 314 \text{ s}^{-1}. \]
Droplet Form Factor & Inter-Droplet Structure Factor

• Scattering Intensity $I(q)$:

$$I(q) = \left< \sum_{i,j} f_i(q) f_j(q) \exp[i \mathbf{q} \cdot (\mathbf{r}_i - \mathbf{r}_j)] \right>$$

- $\mathbf{q}$: the scattering wavevector
- $f$: form factor amplitude
- $\mathbf{r}_i, \mathbf{r}_j$: droplet positions
- $\langle \ldots \rangle$: ensemble average

uniform droplet shape and size

$$I(q) = f(q)^2 \left< \sum_{i,j} \exp[i \mathbf{q} \cdot (\mathbf{r}_i - \mathbf{r}_j)] \right>$$

$I(q) = F(q) S(q)$

$F(q) = f(q)^2$: droplet form factor

$S(q) = \left< \sum_{i,j} \exp[i \mathbf{q} \cdot (\mathbf{r}_i - \mathbf{r}_j)] \right>$: inter-droplet structure factor
Shear Rate-Dependent Droplet Deformation

• Intensity anisotropy factor $\chi_1 = \frac{I_{RP}}{I_{RP}+I_{LP}}$

: droplet form factor $\leftrightarrow$ shape and orientation

$\left(30 \leq \gamma_{\text{max}} \leq 100; \ 0.1 \leq f(\text{Hz}) \leq 1.5\right)$

$\delta = 0.011$
$m = 4.1 \text{ s}$

$\chi = 0.5 + \delta + m \cdot 10^{-4} \dot{\gamma}$.

Average droplet shape and orientation depends mainly on the shear rate.

• Deformed droplets $\approx$ tilt ellipsoids
(the Rayleigh-Gans theory)
Tilt Ellipsoid Model: Rayleigh-Gans Theory

Simulation:

\[ r_0 = 1.117 \, \mu m \]
\[ a = 0.950 \, \mu m; \quad b = 1.314 \, \mu m; \]
\[ c = 1.117 \mu m \]

Aspect ratios: \( b/a = 1.38; \quad c/a = 1.18 \)
\[ l = 2.28 \, \mu m; \quad \theta = 45^\circ \]

- HCP monolayer of 70 ellipsoids
- Average of 200 cases
Primary and Secondary Bragg Spots

- $\chi_1: (R_1, R_2, L_1, L_2)$
  primary Bragg spots

- $\chi_2: (r, l)$

- $\chi_3: (mr_1, mr_2, ml_1, ml_2)$
  secondary Bragg spots

$\phi = 0.70; \ \gamma_{\text{max}} = 100; \ f = 0.5 \text{ Hz.}$

Recorded @ 30FPS; played @ 15FPS
Phase-Resolved Peak Intensities

- Primary and secondary Bragg peak intensities:

\[ I_{\text{MP}} \]
\[ I_{\text{LP}} \]
\[ I_{\text{RP}} \]
\[ I_{\text{mlp}} \]
\[ I_{\text{mrp}} \]

\[ \phi = 0.75 ; \quad \gamma_{\text{max}} = 100 ; \quad f = 0.7 \text{ Hz.} \]

Scattering Intensity Anisotropy Factors

\[
\begin{align*}
\chi_1 &= \frac{I_{RP}}{I_{RP} + I_{LP}} \\
\chi_2 &= \frac{I_{rp}}{I_{rp} + I_{lp}} \\
\chi_3 &= \frac{I_{mrp}}{I_{mrp} + I_{mlp}}
\end{align*}
\]

- Linear fit to \( \chi \)'s: \( \dot{\gamma} > 100 \text{s}^{-1} \)
  \[
  \chi = 0.5 + \delta + m \cdot 10^{-4} \dot{\gamma}.
\]

- Graphs showing plots of \( \chi_1, \chi_2, \chi_3 \) vs. \( \dot{\gamma} \) with linear fits for different values of \( \phi \):
  - \( \phi = 0.75 \): \( \chi_1 \), \( \chi_2 \), \( \chi_3 \)
  - \( \phi = 0.70 \): \( \chi_1 \), \( \chi_2 \), \( \chi_3 \)
  - \( \phi = 0.66 \): \( \chi_1 \), \( \chi_2 \), \( \chi_3 \)
  - \( \phi = 0.62 \): \( \chi_1 \), \( \chi_2 \), \( \chi_3 \)

\( \dot{\gamma} / \text{s}^{-1} \) (30 \( \leq \gamma_{\text{max}} \leq 100 \); 0.1 \( \leq f(\text{Hz}) \leq 1.5 \))
**φ-Dependence of Droplet Deformation**

\[ \chi = 0.5 + \delta + m \cdot 10^{-4} \dot{\gamma}. \]

\[ \phi_g \approx 0.58: \text{glass forming } \phi \]

\( \delta \neq 0: \text{inter-droplet interaction} \)

- **Tilt ellipsoid model:**
  \( (a/r_0, b/r_0, c/r_0, \theta); \)
  \( \text{volume: } r_0^3 = abc \)

  Independent variables:
  two aspect ratios and tilt angle \( \theta \).

  **Fit results:** \( \chi_1(X), \chi_2(+), \chi_3(\ast) \)

  \( (a/r_0, b/r_0, c/r_0, \theta)_\phi = (1.2, 0.88, 0.95, 42^\circ)_{0.62}; \)
  \( (1.22, 0.85, 0.97, 28^\circ)_{0.66}; (1.23, 0.8, 1.01, 26^\circ)_{0.70}; \)
  \( (1.24, 0.79, 1.02, 25^\circ)_{0.75} \)
Shear-History-Dependent Structures

Static
Scattering patterns
at $\psi = 0$
($\gamma = 0; \dot{\gamma} = 0$)

Dynamic
Scattering patterns
at $\psi = \pi/2$
($\gamma = \pi/2; \dot{\gamma} = 0$)

$\phi = 0.70; \dot{\gamma} = 0$

$\gamma_{\text{max}} (s^{-1}) \equiv 2\pi \cdot f \cdot \gamma_{\text{max}}$
Volume Fraction & Shear History Dependences

Increasing inter-droplet interaction

Increasing randomness in droplet positions (more room to wiggle)

\[ \psi = \frac{\pi}{2} \]

\[ \psi = 0 \]

\[ \psi = \frac{\pi}{2} \]

\[ \psi = 0 \]

\[ \gamma = \gamma_{\text{max}} \sin \psi; \quad \psi = 2\pi f t \]

\[ \dot{\gamma} = \dot{\gamma}_{\text{max}} \cos \psi \]

\[ \dot{\gamma}_{\text{max}} = 2\pi \cdot f \cdot \gamma_{\text{max}} \]

\[ \dot{\gamma} = 44 \text{ s}^{-1} \]

\[ \dot{\gamma} = 220 \text{ s}^{-1} \]

\[ \gamma_{\text{max}} = 70, \quad f = 0.1 \text{ Hz} \]

\[ \gamma_{\text{max}} = 70, \quad f = 0.5 \text{ Hz} \]
Jamming and Un-jamming Regimes for Droplet Deformation and Emulsion Structure

\[ |\dot{\gamma}| \leq \dot{\gamma}_s \quad \text{soft-jamming} \]

\[ |\dot{\gamma}| \geq \dot{\gamma}_s \quad \text{Un-jamming; Sliding HCP layers} \]

\[ 30 \leq \gamma_{\text{max}} \leq 100; \quad 0.1 \leq f(\text{Hz}) \leq 1.5 \]
Jamming and Un-jamming of Concentrated Droplets of Uniform Size

\( \phi > \phi_{MRJ} \approx 0.64 \)

- Hard Spheres: \( \phi \leq 0.74 \)
  - Initially ordered spheres
  - Maximum \( \gamma < 1 \).
  - **Spheres jammed.**

- Deformable Droplets: \( \phi \leq 0.74 \)
  - Initially ordered droplets yielding
  - Unlimited \( \gamma \).
  - **Droplets not jammed.**
    (Droplets deform.)

*Effect of large-\( \gamma \) shear on interaction, structure, deformation?
Droplet Deformation and Restructuring

- Lissajous figure of shear oscillation

\[ \gamma = \gamma_{\text{max}} \sin \psi; \quad \psi = 2\pi f t \]
\[ \gamma = \gamma_{\text{max}} \cos \psi \]

\[ |\Delta \gamma_s| = \gamma_{\text{max}} \left(1 - \sqrt{1 - \left(\frac{\gamma_s}{\gamma_{\text{max}}}ight)^2}\right) \]

Force chain buckling

Sliding HCP layers

Shear causes disorder.

Shear induces order.
Volume Fraction & Shear History Dependences

\[ \psi = \frac{\pi}{2} \]

Increasing inter-droplet interaction

\[ \gamma_{\text{max}} = 70; \quad f = 0.1 \text{ Hz} \]

\[ \Rightarrow |\Delta \gamma_s| \approx 70 \]

\[ \gamma_{\text{max}} = 70; \quad f = 0.5 \text{ Hz} \]

\[ \Rightarrow |\Delta \gamma_s| \approx 1 \]

\[ \dot{\gamma}_s \approx 30 \text{ s}^{-1} \text{ from exp.} \]

\[ |\Delta \gamma_s| = \gamma_{\text{max}} \left( 1 - \sqrt{1 - (\dot{\gamma}_s / \dot{\gamma}_{\text{max}})^2} \right) \]

\[ \dot{\gamma}_{\text{max}} = 2\pi \cdot f \cdot \gamma_{\text{max}} \]
Shear-History-Dependent Structures

\[ |\Delta \gamma_s| = \gamma_{max} \left(1 - \sqrt{1 - \left(\dot{\gamma}_s / \dot{\gamma}_{max}\right)^2}\right) \]

\[ \dot{\gamma}_{max} = 2\pi \cdot f \cdot \gamma_{max} \]

Const. \( \dot{\gamma}_{max} \Rightarrow f \uparrow, \gamma_{max} \downarrow \)

\( \Rightarrow |\Delta \gamma_s| \downarrow. \)
Conclusion

- **Phase-resolved shear oscillation light scattering** for investigating droplet deformation, ordering/disordering, jamming/un-jamming at high shear rates and shear strains (difficult with optical microscopy).

- **Shear-induced & shear-history-dependent ordering and disordering** of concentrated emulsions under oscillatory shear. \((\gamma_{\text{max}}, \dot{f}, \psi)\)-dependent

- **Connection between droplet deformation and restructuring**

Funding: Chevron, Human Energy, hard microfluidics
Droplet Deformation and Restructuring

- A simple mechanism:

\[
\gamma = \gamma_{\text{max}} \sin \psi; \quad \psi = 2\pi ft
\]

\[
\dot{\gamma} = \dot{\gamma}_{\text{max}} \cos \psi
\]

\[
|\Delta \gamma_s| = \gamma_{\text{max}} \left( 1 - \sqrt{1 - (\dot{\gamma}_s / \dot{\gamma}_{\text{max}})^2} \right)
\]

0 \approx \dot{\gamma} < \dot{\gamma}_s \quad \text{soft-jamming}

- Force chain buckling

Shear causes disorder.

\dot{\gamma} > \dot{\gamma}_s \quad \text{Un-jamming}

- Sliding HCP layers

Shear induces order.
Future Works

- Detailed investigation of the regime at $\dot{\gamma} \approx \dot{\gamma}_s$; “fine structures”; middle peaks
- Shear melting at high $\dot{\gamma}$; generalization of the model
- Even at higher volume fraction: bi-liquid foams
- Effect of viscosity ratio, surfactant, etc on droplet deformation, structure, and coalescence
- Phase-resolved rheology
- Real-space observation of shear-induced restructuring
- Brighter laser or larger droplets to observe higher-order Bragg spots
- Modeling deformation and restructuring of concentrated droplets $\chi$’s; force-chain buckling; non-ellipsoidal deformation; zig-zag motion; defects; …
Jayden Huang
7 months old
Happy New Year
Shear-History-Dependent Structures

Static Scattering patterns at $\psi = 0$ ($\gamma = 0; \dot{\gamma} = 0$)

Dynamic Scattering patterns at $\psi = \pi/2$ ($\gamma = \pi/2; \dot{\gamma} = 0$)

$\dot{\gamma}_{\text{max}} (s^{-1}) = 2\pi \cdot f \cdot \gamma_{\text{max}}$

$\phi = 0.70; \dot{\gamma} = 0$
\[ \phi = 0.70; \quad \gamma_{\text{max}} = 70; \quad f = 0.1 \text{Hz.} \]

\[ \gamma = \gamma_{\text{max}} \sin \psi \]

\[ \dot{\gamma} = 2\pi f \gamma_{\text{max}} \cos \psi \]

\[ \psi = 2\pi ft \]

4X real speed (7.5FPS)
Phase-Resolved Peak Intensities

\[ \phi = 0.70; \quad \gamma_{\text{max}} = 100; \quad f = 0.5 \text{ Hz}. \]

\[ I_{RP}(\circ), \quad I_{MP}(\blacktriangleleft), \quad & I_{LP}(\times) \quad \text{v.s. phase } \psi \]
Phase-Resolved Bragg Peak Intensities

- Primary and secondary Bragg peak intensities:

\[
\begin{align*}
I_{MP} & , I_{RP} \\
I_{LP} & , I_{mLP} \\
I_{mRP} & , I_{lp} \\
I_{rP} & , I_{mLP}
\end{align*}
\]

\[\phi = 0.75; \quad \gamma_{max} = 100; \quad f = 0.7 \text{ Hz.}\]
### Volume Fraction & Shear History Dependences

$$\dot{\gamma}_s \approx 30 \, s^{-1} \quad \text{from exp.}$$

$$|\Delta \gamma_s| = \gamma_{\max} \left(1 - \sqrt{1 - (\dot{\gamma}_s / \dot{\gamma}_{\max})^2}\right)$$

$$\dot{\gamma}_{\max} = 2\pi \cdot f \cdot \gamma_{\max}$$

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$\gamma_{\max} = 70, \ f = 0.1 , \text{Hz}$</th>
<th>$\gamma_{\max} = 70, \ f = 0.5 , \text{Hz}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\dot{\gamma} = 0 , s^{-1}$</td>
<td>$\dot{\gamma} = 0 , s^{-1}$</td>
</tr>
<tr>
<td>0.75</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>0.70</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>0.66</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>0.62</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>0.55</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Increasing inter-droplet interaction

$$\gamma_{\max} = 70; \ f = 0.1 \, \text{Hz}$$

$$\Rightarrow \ |\Delta \gamma_s| \approx 70$$

$$\gamma_{\max} = 70; \ f = 0.5 \, \text{Hz}$$

$$\Rightarrow \ |\Delta \gamma_s| \approx 1$$
Analysis of Scattering Pattern

- Azimuthally averaged Intensity:
\[ I_A(q,t) = \int_{R+M+L} d\varphi_q I(\bar{q},t); \quad q = |\bar{q}|. \]

- Cos(6\varphi_q)–weighted Intensities:
\[ I_R(q,t) = \int_R d\varphi_q I(\bar{q},t) \cos 6\varphi_q. \]
\[ I_M(q,t) \text{ and } I_L(q,t) \text{ likewise defined.} \]

\[ \frac{I_R}{I_A}, \frac{I_M}{I_A}, \text{ and } \frac{I_L}{I_A} : \text{ a measure of peak-to-background ratio.} \]

\[ \frac{I_{RP}}{I_{LP}} : \text{ droplet deformation.} \]
Shear-induced Order and Disorder

\( i_{RP}, i_{LP}, i_{MP} \):
Bragg peak intensities normalized by the azimuthally-averaged intensity
Shear-induced Order and Disorder

Max. of \( \frac{I_R}{I_A}, \frac{I_M}{I_A}, \) and \( \frac{I_L}{I_A} \):

- Dg, Dm: all \( \leq 0.1 \)
- H6: all > 0.1
- H4: Max. of \( \frac{I_M}{I_A} \) < 0.1

\( \phi = 0.70; \ \dot{\gamma} = 0 \)

\( \dot{\gamma}_{\text{max}} (s^{-1}) \equiv 2\pi \cdot f \cdot \gamma_{\text{max}} \)
Introduction: Making Emulsions

* Crucial elements for making emulsions:
  
  - Two immiscible liquids such as oil and water
  - Emulsifying agent (surfactant): SDS (sodium dodecyl sulfate), lipids
  - Mechanical force for mixing and dispersing (**kinetically stable**)

Parameters: droplet volume fraction; surfactant type; applied stress

* Examples of food emulsions:
  Butter (W/O); Mayonnaise (O/W); Salad dressing (O/W)
Dimensionless Numbers

\[ \rho \approx 1 \text{ g/cm}^3; \text{ Gap size } h = 100 \mu\text{m}; \text{ Drop size } a \approx 1 \mu\text{m} \]

\[ \mu \approx 600 \text{ cP} \approx 0.6 \text{ Pa} \cdot \text{s}; \sigma \approx 2 \text{ dyn/cm} \]

*Note: no inter-droplet interactions*

\[
\text{Re} = \frac{\text{interia}}{\text{viscous force}} = \frac{\rho V L}{\mu} : \quad \text{Re} = \frac{\rho \cdot \dot{\gamma} \cdot h^2}{\mu} = 0.017 << 1
\]

\[
\text{Ca} = \frac{\text{viscous stress}}{\text{Laplace pressure}} = \frac{\mu \cdot \dot{\gamma}}{\sigma / a} = 0.03 \text{ (for } \dot{\gamma} = 10^2 \text{ s}^{-1}) \sim 0.3 \text{ (for } \dot{\gamma} = 10^3 \text{ s}^{-1})
\]

\[
\tau = \frac{a \cdot \mu}{\sigma} = 0.3 \text{ ms}
\]

\[
\text{Pe} = \frac{\text{convection}}{\text{diffusion}} = \frac{V L}{D} : \quad \text{Pe} = \frac{\dot{\gamma} \cdot a^2}{D} \sim \frac{\mu \dot{\gamma} \cdot a^3}{kT} \sim 1.5 \cdot 10^3
\]

\[ a^2 \sim D \cdot t ; \quad D \sim \frac{kT}{\mu a} \]