Particle sedimentation in emulsions

Experiments with sheared emulsions and emulsions at rest

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Abstract
Understanding migration of particles in emulsions is essential for many industrial applications, like drilling fluids in petroleum industry.
In the first part, we describe an experimental setup which allows the visualization of particles in a transparent emulsion in a Couette cell. We measure the horizontal velocity field in the Couette cell. When the emulsion is at rest, we reconstruct a 3D picture of the emulsion to obtain the height and the position in the gap of each particle.
In the second part, we show experimentally and with a minimal model that particle sedimentation in emulsions at rest cannot be predicted by the classical criterion for spheres embedded in a yield stress fluid. Phase separation processes take place, where a liquid layer forms, and particle sedimentation is enhanced by the emulsion drainage.

Experimental setup to study particle migration in a Couette cell with optical method

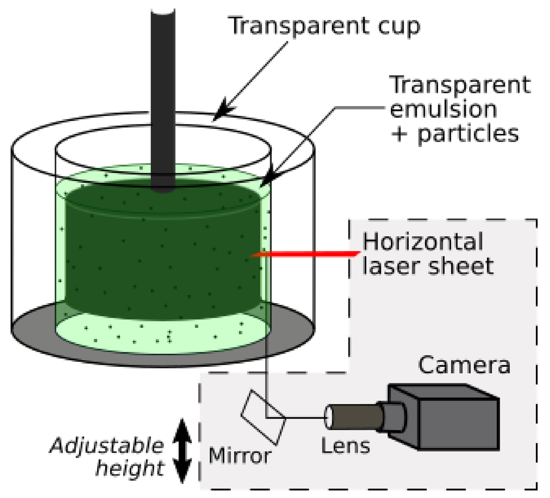
Introduction

Concentrated emulsions are yield stress fluids, i.e. than flow only if the applied stress is above a critical value called yield stress. Particle in sheared yield stress fluids are known to sediment [1], migrate to high shear regions [2] and agglomerate [3].
PIV (particle image velocimetry) has successfully been implemented in a Couette cell to study wall slip of yield stress fluid [4]. Here we describe a similar setup deployed to study particle migration in emulsions.

Materials

Transparent emulsion: Continuous phase is 53wt% of glycerol in DI water with 3wt% TTAB surfactant. Dispersed phase is silicone oil V350.
Particles: diameter from 5 to 100 μm.

Setup



- Couette cell (internal radius 16 mm, gap 1.5 mm, height 16 mm).
- Adjustable height of observation
- Field of view 3 * 4 mm, resolution 340 px/mm.
- Controllable temperature

Figure 1: Schema of the setup

Velocity profiles obtained by PIV

In PIV (Particle Image Velocimetry), a pair of pictures of particles are cross-correlated to calculate particle displacement at each point of the image, and therefore the velocity field.

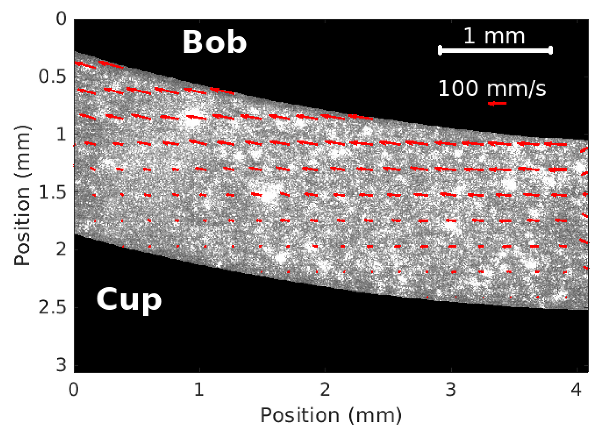


Figure 2: Velocity field (in red) obtained with PIV at 100 s^{-1}, superimposed with one of the corresponding pictures of the particles.

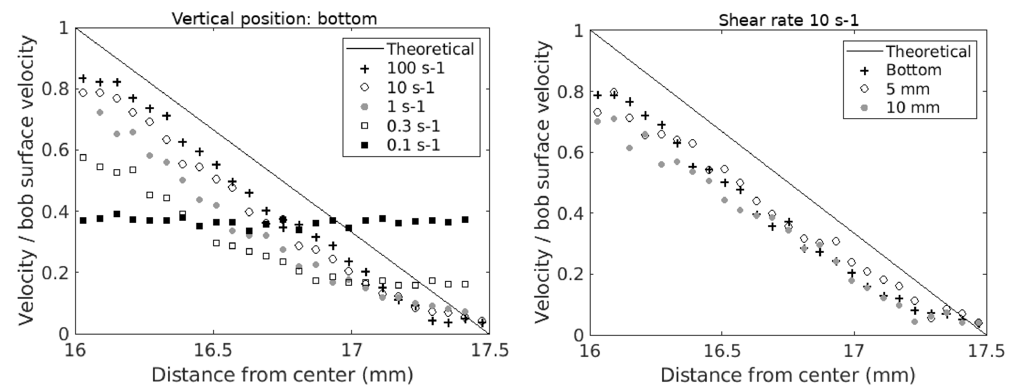


Figure 3: Velocity profiles deduced from PIV.

- Wall slip is occurring
- Plug flow if $\dot{\gamma} \lesssim 1 s^{-1}$
- Velocity profiles do not depend on vertical position

3D reconstructions

A 3D image is reconstructed from 2D pictures taken at different heights (6 pictures/mm). We deduce the radial and vertical position of each particle.

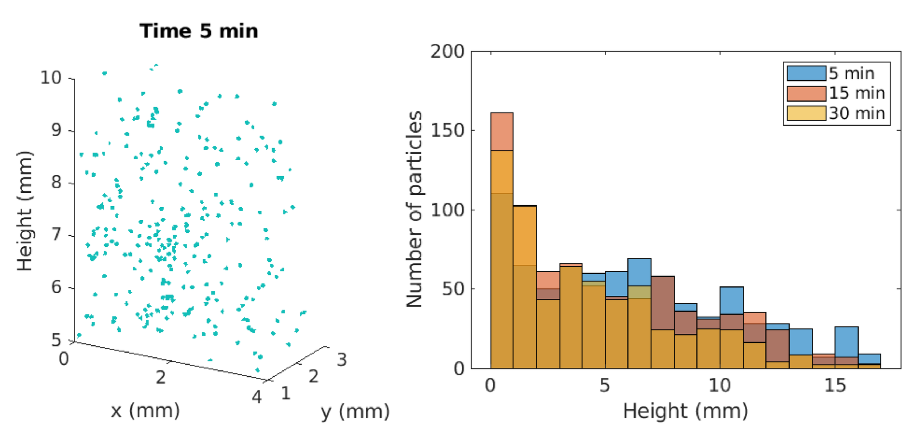


Figure 4: Example of 3D reconstruction with 40 μm diameter particles and evolution of vertical positions with time.

Conclusion

- We manufacture transparent emulsions to observe suspended particles in a Couette cell with an optical technique.
- We use PIV to measure the effective shear rate in the Couette gap. We observe that plug flow occurs at low shear rate ($< 1\ s^{-1}$).
- By scanning vertically a portion of the Couette cell, we obtain the 3D reconstruction of particles in the gap.

References

[1]: Ovarlez & *al.*, *J. Non-Newton. Fluid* 177-178, (2012): 19-28
[2]: Gauthier & *al.*, *Rheol. Acta* 10, (1971): 344-364
[3]: Michele & *al.*, *Rheol. Acta* 16, (1977): 317-321
[4]: Medina-Banuelos & *al.*, *J. Rheol.* 61, (2017): 1007-1022

Destabilization and phase separation of particle suspensions in emulsions.

Manuscript submitted to Soft Matter and deposited on ArXiv.

Introduction

In continuous yield stress fluids, spherical particles sediment if the yield stress is below a critical value [1]:

$$\tau_{y,s} = \frac{1}{21}\Delta\rho g d, \qquad (1)$$

where $\Delta\rho$ is the density difference between the particles and the fluid and d is the particle diameter. Here we show that this criterion is not enough to predict particle sedimentation in concentrated emulsions. We must take into account drainage of continuous phase in the emulsion.

Materials and methods

All samples are prepared from the same mother direct emulsion, they differ by the amount of particle Φ_p and the initial volume fraction of continuous phase in the emulsion, φ_i.

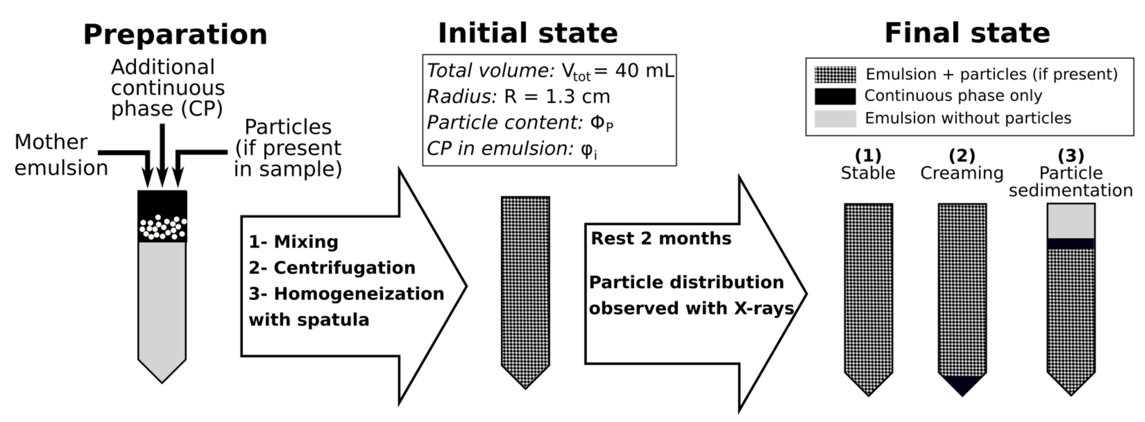


Figure 5: Example of 3D reconstruction with 40 μm diameter particles and evolution of vertical positions with time.

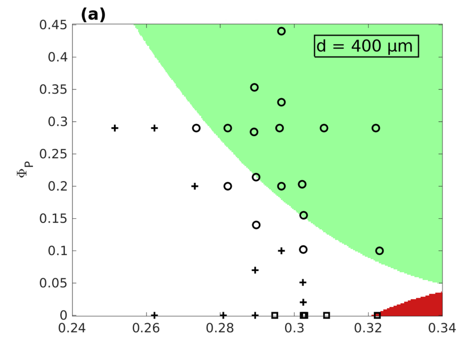
Drainage model

The volume content of continuous phase φ is calculated at each height z in the sample. Sedimentation occurs only if φ reaches locally φ_s, obtained from Eq. 1.
In the *static approach*, the equilibrium $\varphi(z)$ profile is calculated analytically by balancing hydrostatic pressure with osmotic pressure, i.e. pressure due to droplet deformation, similarly to [2]. In the *dynamic approach*, we solve explicitly Darcy's law and the continuity equation to calculate flow velocity of continuous phase.

Hypotheses:

- As long as $\varphi < \varphi_s$, particles are stuck by droplets.
- Droplets and particles from together the dispersed phase. Dispersed phase is lighter than the continuous phase for low amount of particles, and becomes denser for particle volume content $\Phi_P \gtrsim 5\%$.
- The osmotic pressure is not affected by the particles.

Static approach results



- Stability diagram hardly depends on particle size.
- When particle sedimentation occurs, a layer of continuous phase also appears on the top of the sample.

Figure 6: Experiments: stable (crosses), creaming (squares), and particle sedimentation on top (circles). Model: stable (white), particle sedimentation on bottom (red) and particle sedimentation on top (green).

Settling dynamics

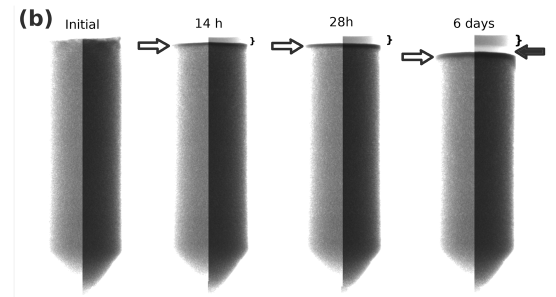


Figure 7: Spatio-temporal distribution of particles in an unstable samples shown from X-ray measurements. Each image is composed of two pictures corresponding to different X-ray intensities. The empty arrow shows the formation of a dense particle layer, and the black arrow, a liquid layer.

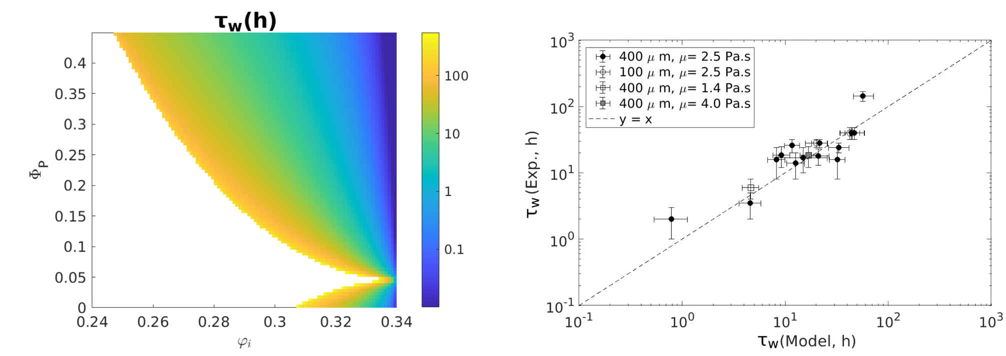


Figure 8: Waiting time before sedimentation starts. Left: model calculation. Right: comparison of experimental and theoretical values.

Conclusion

- Our minimal model predicts satisfactorily particle sedimentation in emulsions.
- A large particle content increases emulsion drainage and enhances particle sedimentation.
- A moderate amount of particle can prevent drainage.

References

[1]: Beris & *al.*, *Journal of Fluid Mechanics* 158, (1985), 219–244
[2]: Maestro & *al.*, *Soft matter* 9, (2013), 2531