Flow-induced deformation of droplets, vesicles and red blood cells

Stefano Guido
Background

Flow behavior of deformable particles, both individual and collective, is relevant in a range of applications.

Droplets
Blood cells
Vesicles

Emulsions, polymer blends
Lab-on-chip diagnostics, single cell analysis
Drug delivery

Flow-induced morphology evolution of droplets is governed by two (apparently) simple processes

Drop deformation and breakup

Collision and coalescence

Our starting point is an isolated droplet (or a binary collision) under simple (laminar) shear flow in the small deformation limit.
Some issues on (laminar) flow behavior of droplets

- How do isolated droplets deform and breakup under steady and transient (unbounded) shear flow?

- How does geometrical confinement affect droplet deformation and breakup?

- What is the effect of viscoelasticity of the component fluids?

- What can we learn from isolated droplets on collective flow behavior of concentrated systems (e.g., emulsions and polymer blends)?

- How can coalescence be investigated under shear flow?

- What is the effect of surfactants?
Starting point: small deformation theory

Nondimensional parameters governing drop deformation

\[ Ca = \frac{\eta_c \dot{\gamma} R}{\sigma} \]

Capillary number

\[ \lambda = \frac{\eta_d}{\eta_c} \]

Viscosity ratio

\[ \sigma \quad \text{interfacial tension} \]

\[ \eta_c \text{ and } \eta_d \text{ viscosities of continuous and droplet phase} \]

Main theory predictions (under steady state conditions)

\[ \left\{ \begin{array}{l}
\frac{r_{\text{MAX}}}{r_0} = 1 + f_1(\lambda)Ca + f_2(\lambda)Ca^2 \\
\frac{r_{\text{MIN}}}{r_0} = 1 - f_1(\lambda)Ca + f_2(\lambda)Ca^2 \\
\frac{r_z}{r_0} = 1 + f_3(\lambda)Ca^2
\end{array} \right. \]

Experiments show that droplets take an ellipsoidal shape under shear flow

Effects of confinement

Wall effects tend to stabilize shape and hinder breakup

\[ h \approx 2R \]

Data in agreement with small deformation theory (Shapira and Haber, Int. J. Fluid Mechanics, 1990)

\[ D_w = D_T \left[ 1 + C_s \left( \frac{a}{H} \right)^3 \frac{1 + 2.5 \lambda}{1 + \lambda} \right] \]

h \approx 2R, Ca = 0.5
Rheological properties of the fluid components can be another source of viscoelasticity apart from the interfacial tension.

Additional physical quantities:

\[ N_1 = T_{11} - T_{22} = \Psi_1 \dot{\gamma}^2, \quad N_2 = T_{22} - T_{33} = \Psi_2 \dot{\gamma}^2 \]

New nondimensional parameter:

\[ p \equiv \frac{W}{Ca^2} = \frac{\psi_1 \sigma}{2r_0 \eta^2} \quad (\approx 1 \text{ for significant non-Newtonian effects}) \]

Outer fluid: non-Newtonian (Boger), Inner fluid: Newtonian

\[ Ca = 0.4 \quad \lambda = 1 \]

Small deformation theory shows that drop orientation is directly linked to \( N_1 \)

Inner fluid: Newtonian, Outer fluid: non-Newtonian (Boger)
Isolated droplet deformation predictions hold true also in a concentrated system provided that the actual system viscosity is used to calculate $Ca^*$:

$$Ca^* = \frac{\eta_{\text{blend}} R \dot{\gamma}}{\sigma}$$

Shear banding

Binary collisions and coalescence

Drop collisions is irreversible mechanism for drop dispersion

Coalescence between two droplets

The resulting drop is broken up and the daughter drops are made to collide again

Upon increasing Ca, a critical condition ($C_{a_{cr}}$) is reached where shape becomes unstable.

Scaling arguments show that breakup time scales as

$$\tau(Ca) \propto \frac{1}{\sqrt{C_{a_{cr}} - Ca}}$$

and that daughter drop size scales with critical drop size, but fragment distribution is still an open issue.

Effect of surfactants

- Emulsions are often made with “high” surfactant (and co-surfactants) concentration to improve stability or performance.

- High surfactant concentrations are associated with complex microstructures and a strong interfacial viscoelasticity, which make measurement of interfacial properties quite difficult with classical methods.

- A “simplified” binary system could be just surfactant and water (surfactant droplets or vesicles).

Microfluidics tensiometry
Surfactant multilamellar vesicles (SMLVs)

Most work in the literature is devoted to equilibrium microstructures (e.g., micelles, bicontinuous sponge phase, lamellar phases and vesicles) as a function of concentration and temperature.

Main issue: how can SMLVs deform and breakup under the action of flow?

Analogy with droplets and capsules

\[ Ca = \frac{\eta \dot{\gamma} R}{\sigma} \]
\[ \lambda = \frac{\eta d}{\eta} \]
\[ \sigma = 10^{-4} \text{ N/m} \]

Vesicles deform at constant volume, but not at constant area


SMLV microstructure under flow

Scale bars = 100 µm

Parabolic Focal Conic domains (a defect of smectic A liquid crystals)

Ch. S. Rosenblatt et al., Le Journal De Physique 38, 1105 (1977)

Red blood cells in microcirculation

RBC cells can be regarded as fluid-filled sacs with an excess area, enclosed by a lipid bilayer (inextensible) membrane with an underlying protein network.

Flow-induced phenomena: clustering, deformation and aggregation

- What is the relative importance of RBC membrane parameters, including membrane viscosity?
- How do RBCs interact with endothelium and with microparticles (margination)?
- What are the pathological effects of altered RBC deformability and aggregability?
RBC stationary shape

RBC flow behavior in a microcapillary is well described by (T. W. Secomb, R. Skalak, N. Ozkaya and J. F. Gross, J. Fluid Mech., 1986, 163, 405–423)

- considering the cell as axisymmetric
- using lubrication theory to model flow in the gap between cell and walls
- accounting for elastic deformation only (no viscous contribution)
- taking unstressed shape as that of an inflated sphere

Theoretical predictions, Secomb et al. 1986

At high velocities only an isotropic in-plane tension is considered (bending and shear being negligible)
Different shapes depending on initial RBC position and orientation

Characteristic relaxation time of about 0.1 s (healthy cells)

It decreases with increasing cell rigidity
RBC flow in a diverging channel

RBC deformation is well described by a Kelvin-Voigt model with a shear modulus $\mu$ and a membrane viscosity $\eta$

\[ T = \frac{\mu}{2} \left[ \left( \frac{\lambda}{\lambda_{fin}} \right)^2 - \left( \frac{\lambda}{\lambda_{fin}} \right)^{-2} \right] + \frac{2\eta}{\lambda} \frac{\partial \lambda}{\partial t} \]

Membrane viscous contribution is dominant over inner cell viscosity ($\mu_{int}/\mu = 0.015$, Secomb and Hsu, 1996) and over elasticity at time scales $< \eta/\mu = 0.1$ s

$\mu = 0.006$ dyn/cm
$\eta = 0.055$ cP
Effect of a glycocalyx model system

Glycocalix
- Layer of glycopolymers bound to endothelial cells membrane
- Thickness of 100 – 1000 nm
- Influence on the resistance to flow in microcirculation
- Involvement in microvascular diseases

Polymer brushes
pHEMA

RBCs velocity decrease in hairy capillaries is higher than expected from lumen reduction

Highlighted in Physics Today, April 2014

Lanotte et al., Biomicrofluidics 2014
Lanotte et al., Langmuir 2012
Conclusions

- The flow behavior of deformable particles, such as droplets, vesicles and red blood cells, shows several analogies from the phenomenological point of view.

- Particle deformation can be modelled in terms of one (or more capillary) number(s), depending on the rheological properties of the interface.

- Measurement of interfacial viscoelasticity is a complex task.
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