Abstract

Drop deformation in uniform electric fields is a classic problem. The pioneering work of G. I. Taylor demonstrated that for weakly conducting media, the drop fluid undergoes a toroidal flow and the drop adopts a prolate or oblate spheroidal shape, the flow and shape being asymmetrically aligned with the applied field. However, recent studies have revealed a nonaxisymmetric rotational mode for drops of lower conductivity than the surrounding medium, similar to the rotation of solid dielectric spheres observed by Quincke in the 19th century. We have performed an experimental and theoretical study of this phenomenon in DC fields.

The critical electric field, drop inclination angle, and rate of rotation are measured. For small, high viscosity drops, the threshold field strength is well approximated by the Quincke rotation criterion. Reducing the viscosity ratio shifts the onset for rotation to stronger fields. The drop inclination angle increases with field strength. The rotation rate is approximately given by the inverse Maxwell-Wagner polarization time. We also observe a hysteresis in the tilt angle for low-viscosity drops.

We have also considered drops encapsulated by complex interfaces such as lipid bilayer membranes. A comparison between the behavior of drops and giant vesicles (cell-size lipid membrane sacs) highlights new features due to the membrane electromechanics.

A DROP in a uniform DC electric field

Interface charging

Weak fields

- Tangential electric stress induces fluid motion
- Axisymmetric toroidal flow
- Electric pressure \( \propto \) deformation
- Charge (constrained only with weakly conducting media)

Rotation of a fluid droplet? (fluid not solid!)

Characteristics:
- Fluid rotation
- Stationary drop shape
- Oblique orientation

Experiment

Continuous phase: castor oil (dielectric constant \( \epsilon_{\text{out}} \))

Transition to rotation

Critical electric field normalized by Quincke theory

High viscosity \( \Rightarrow \) Quincke rotation (rigid sphere)

Lower viscosity ratio \( \Rightarrow \) charge convection

- Stronger charge convection reduces dipole strength
- Greater field strength is required to generate rotation

Large drops:
- Greater disruption to electric field because of larger deformation

Ongoing work: theory

A VESICLE in a uniform DC field

The lipid membrane has more complex electromechanics than fluid-fluid interfaces.

- Impermeable to ions \( \Rightarrow \) capacitor
  \[ C_m = \frac{1}{3\pi\eta R^2} \]
  \( \sigma = 0 \), \( \mu = 0 \), \( \nabla \phi = 0 \)

1. 2D area-incompressible fluid
2. 2D area-incompressible fluid
3. "soft" bending modulus \( \kappa \), \( \mu \)

Analytical solutions: quasi-spherical vesicle

Transitions: Deformation?

Shapes in electric field?

Laplace’s law

Tension is a dynamic variable that has to be self-consistently determined along with the change in shape

\[ \tau(\theta, \phi) = \frac{1}{2} \mu \left( \nabla^2 \phi - 4H \nabla^2 \phi + 2\nabla \phi \right) \]

Sokolke-Stokes equation for the fluid motion and the Laplace equation for the electric potential.

Ongoing work: vesicles in a DC pulse?