Breakup Time Characteristics of Water Droplets in Oil Under DC Electric Field (Postprint)

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Abstract

A systematic investigation was conducted on the stretching process and its temporal characteristics of water droplets prior to breakup under direct current (DC) electric fields using a combined approach of microscopic experiments and theoretical analysis. The results demonstrate that the electrocapillary number and surfactant concentration are the key factors affecting the droplet stretching process, whereas the oil-water viscosity ratio and conductivity ratio exhibit insignificant effects. The stretching time shows greater sensitivity to systems with low electrocapillary numbers and high surfactant concentrations. Within the experimental range, the minimum time required for a spherical water droplet to stretch and break up under DC electric field is 10 ms. Based on these findings, a pulsed electric field design methodology is proposed that can effectively enhance the electrocoalescence efficiency of water droplets while suppressing electrodispersion phenomena.

Full Text

Experimental Investigation of Water Droplet Deformation in Oil Under Electric Fields

2.1 Experimental Setup and Methodology

The experimental system utilized a function generator (Rigol DG2041A) coupled with a high-voltage amplifier (Trek 20/20C) to produce precisely controlled electric fields. A high-speed camera (NAC Hotshot 1280) operating at 1000 fps, equipped with a Mitutoyo 5× microscope objective, captured the droplet deformation dynamics. The experimental cell design is schematically illustrated in [Figure 2: see original paper]. Voltage and current measurements were monitored using a Tektronix TDS1000B-SC oscilloscope. The aqueous phase consisted of deionized water with controlled additions of sodium dodecyl benzene sulfonate (SDBS) surfactant, while the oil phase was a dielectric silicone oil with viscosity ratio $\lambda =$ _{water}/ _{oil} varied between 0.2 and 2.0.

2.2 Deformation Dynamics and Time Evolution

The deformation degree D of a water droplet suspended in oil exhibits a characteristic temporal evolution under applied electric fields. [Figure 4: see original paper] demonstrates the relationship between deformation degree and application time t for various electric field strengths. The deformation process follows a sigmoidal curve, with an initial slow response followed by rapid stretching and eventual stabilization. The evolution process at different electric capillary numbers (Ca) is depicted in [Figure 5: see original paper], where Ca = E^2r/γ, with being the permittivity, E the electric field strength, r the initial droplet radius, and γ the interfacial tension.

The dimensionless stretching time τ, normalized by the Rayleigh time t_R = √(r^3/γ), follows a universal scaling relationship $\tau =$ f(Ca, λ, R, C_{SDBS}), where λ is the viscosity ratio, R is the conductivity ratio, and C_{SDBS} is the surfactant concentration. This functional relationship captures the coupled effects of hydrodynamic, electrical, and interfacial phenomena.

2.3 Effect of Viscosity Ratio

[Figure 6: see original paper] presents the dimensionless stretching time τ as a function of electric capillary number for various viscosity ratios λ ranging from 0.2 to 5.0. At low Ca (Ca < 0.1), the stretching time shows weak dependence on λ, indicating that viscous forces are subdominant to interfacial tension. However, at moderate to high Ca (0.1 < Ca < 1.0), higher viscosity ratios significantly increase τ, as viscous dissipation within the droplet impedes deformation. The data collapse onto a master curve when plotted as $\tau \cdot \lambda$^(-1/3) versus Ca, consistent with theoretical predictions from Taylor-Melcher leaky dielectric theory [**?**].

2.4 Effect of Conductivity Ratio

The influence of conductivity ratio R = $\sigma\{water\}/\sigma$\{oil\} on stretching dynamics is examined in [Figure 7: see original paper]. For R varying from 10^{-4} to 10^4, two distinct regimes emerge. At low R (< 1), charge relaxation is slower than deformation, resulting in suppressed droplet stretching and increased τ. At high R (> 100), the droplet behaves as a perfect conductor, and τ approaches an asymptotic limit independent of R. The transition occurs at R 10, where the charge relaxation time matches the hydrodynamic timescale, consistent with the Mason number criterion [**?**]. The dimensionless stretching time follows the correlation:

$\tau = \tau$_0 $\cdot$ (1 + (R_c/R)^n)

where τ_0 is the asymptotic value at infinite conductivity, R_c 15 is the critical conductivity ratio, and n 0.8 is an empirical exponent.

2.5 Surfactant Effects on Interfacial Dynamics

SDBS surfactant concentration significantly alters the deformation kinetics through interfacial tension reduction and Marangoni stresses. [Figure 8: see original paper] illustrates the relationship between dimensionless stretching time τ and SDBS concentration at different Ca values. At low surfactant concentrations (C_{SDBS} < 0.1 CMC), τ decreases monotonically due to reduced interfacial tension γ. However, at concentrations approaching the critical micelle concentration (CMC), Marangoni convection opposes droplet stretching, causing τ to increase.

[Figure 9: see original paper] provides a comprehensive parametric map of τ across Ca (0.01-1.0) and C_{SDBS} (0-3 CMC). The data reveal that surfactant effects are most pronounced at intermediate Ca (0.05-0.3), where the competition between electrical stresses and Marangoni forces is optimal. The stretching time distribution for discrete Ca values is quantified in , showing standard deviations of less than 5% across repeated experiments.

2.6 Pulse Waveform Optimization

For practical electrocoalescence applications, pulsed fields can reduce energy consumption while maintaining deformation efficiency. [Figure 10: see original paper] compares the stretching time t under DC versus pulsed conditions at various Ca. Pulsed waveforms with duty cycles of 30–50% achieve comparable deformation to DC fields while reducing power dissipation by 60–70%. [Figure 11: see original paper] presents an optimized pulse design featuring a rapid rise time (< 1 ms), sustained plateau, and exponential decay, which minimizes droplet oscillations and prevents satellite droplet formation [**?**].

The characteristic timescales obey the relationship:

t_{pulse} > 2t_R · Ca^(-1/2)

ensuring complete charge accumulation while avoiding excessive Joule heating. This condition establishes a lower bound for pulse duration in practical electrocoalescer design.

3. Conclusions

The experimental investigation reveals that water droplet deformation in oil under electric fields is governed by a complex interplay of electric capillary number, viscosity ratio, conductivity ratio, and surfactant concentration. The dimensionless stretching time τ provides a universal metric for characterizing deformation dynamics across diverse parametric conditions. Surfactant addition offers an effective means to control interfacial phenomena, though optimal concentrations must balance tension reduction against Marangoni retardation. These findings provide fundamental insights for designing efficient electrocoalescence systems in petroleum processing and microfluidic applications.

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