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Turbulent emulsions of hydrophilic and lipophilic surfactants ☆

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ABSTRACT

We investigate the adsorption of hydrophilic and lipophilic surfactants in turbulent oil-in-water emulsions.

1. Brief description

The hydrophilic–lipophilic balance (HLB) of a surfactant quantifies its preferential solubility in either the water or oil phase. This solubility preference directly influences how surfactants adsorb to and desorb from interfaces, thereby affecting their spatial distribution at the interface and within the bulk phases (Bergfreund et al., 2021; Keshavarzi et al., 2024). Using direct numerical simulations (DNS) of turbulent oil-in-water emulsions (i.e., oil droplets dispersed in a water carrier flow), we investigate how the surfactant HLB influences the interfacial distribution of surfactant – a key parameter for controlling emulsion stability (Baù et al., 2025; Liu et al., 2005; Piela et al., 2006; Yi et al., 2024). The surfactant dynamics are modeled using a two-order-parameter phase-field method (Laradji et al., 1992; Soligo et al., 2019a,b; Roccon et al., 2023), which is here extended to account for the effect of preferential solubility. We first examine the topology of the oil droplets and find that it remains largely unaffected. We then focus on the surfactant dynamics, particularly its distribution across the interface and within the two bulk phases. Our results reveal substantial differences in the interfacial surfactant concentration depending on the HLB: oil-soluble (hydrophobic, low HLB) surfactants lead to higher interfacial concentrations compared to water-soluble (lipophilic, high HLB) surfactants. To elucidate the mechanism behind this difference, we analyze surfactant transfer rates between the carrier phase, the interface, and the dispersed phase. For hydrophilic surfactants, the water carrier phase efficiently absorbs surfactant desorbed from the interface, resulting in a higher interface-to-carrier transfer rate. In contrast, for lipophilic surfactants, the oil droplets are less effective at absorbing surfactant, leading to a lower interface-to-droplet transfer rate.

The qualitative figure shows a three-dimensional rendering of the channel flow laden with surfactant-laden drops. Streamlines are used to show the flow field while the interface of the droplets ($\phi = 0$) is colored by the surfactant concentration (white-low; red-high). The left part refers to lipophilic surfactants while the right part to hydrophilic surfactants. For the lipophilic case, the interface is visibly enriched in surfactant (darker orange).

CRediT authorship contribution statement

Alesssio Roccon: Conceptualization, Data curation, Formal analysis, Validation, Visualization, Writing – original draft. **Umberto Baù:** Data curation, Investigation, Methodology, Software. **Francesca Mangani:** Data curation, Formal analysis, Investigation, Methodology. **Alfredo Soldati:** Conceptualization, Funding acquisition, Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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